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TFG TITLE: Flight Test Preparation of a 4D-controller for time constrained Continuous Descent Operations (CDO)

DEGREE: Bachelor's Degree in Air Navigation

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Títol: Preparació d’un controlador 4D per un test de vol d‘una aproximació de descens continu amb restriccions de temps

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Resum

Dins del marc del programa europeu Clean Sky,un test de vol preparat per la DLR (Centre Aeroespacial Alemany) està previst. Davant la previsió d’aquest test de vol, la preparació i possible millora del comportament d’un controlador amb capacitats 4D utilitzat durant una aproximació de descens continu ha estat el principal objectiu d’aquest projecte. La principal tasca a evaluar del controlador 4D és l’enviament d’indicacions al pilot a través d’una interfície home-màquina disponible a bord de l’avió. Aquestes indicacions són les que el pilot posteriorment introduirà en els principals sistemes de guiatge de l’avió per tal de possibilitar el vol d’una aproximació de descens continu amb restriccions de temps al sobrevolar determinats punts de navegació de manera acurada.

La metodologia utilitzada per avaluar la funcionalitat del controlador ha estat l’utilització de diversos entorns de simulació a través dels quals la recopilació de dades i les posteriors observacions s’han dut a terme. Els entorns de simulació es diferencien per la manera de modelar el comportament de l’avió, per les capacitats de simular condicions meteorològiques, així com també per la seva interfície gràfica. A més de la resposta del controlador, s’han realitzat observacions relacionades amb la interacció home-màquina i la robustesa del sistema. En tots els casos, les simulacions han estat en temps real i ≪manuals≫, utilitzant un mètode similar al que el pilot haurà d’executar durant el test de vol.

Els resultats i les observacions extretes a partir de les simulacions realitzades indiquen un bon funcionament del controlador. La precisió en temps obtinguda en el punt de control del descens contínu està dins els marges de temps rellevants des del punt de vista operacional del controlador. L’ús del motor i els aerofrens ha estat acceptable en els escenaris amb interferències exteriors, i nul en els escenaris sense interferències, havent-hi certs canvis segons l’entorn de simulació. Les indicacions enviades pel controlador han estat enviades amb una freqüència considerada acceptable pel pilot que no li causaria una gran càrrega de treball. Aquests i altres resultats obtinguts es mostren al llarg d’aquest projecte.

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Overview

Within the Clean Sky European project, a flight test prepared by the German Aerospace Center (DLR) is foreseen and meant to prove the capability of flying a Continous Descent Operation (CDO) while satisfying a time constraint at a waypoint. In light of this event, the main objective of this project is the preparation and possible improvement of a 4D-Controller that enables this time constrained CDO. The main task of the 4D-Controller that must be evaluated is the transmission of advisories by the controller to a human-machine interface on board the aircraft. These advisories are the ones that the pilot will further on introduce into the main flight guidance systems of the aircraft in order to perform the time constrained CDO.

The methodology used to evaluate the functionality of the controller has been the use of different simulation environments through witch data regarding the controller's behavior has been collected. The distinctive elements between the different simulation environments are the aircraft performance model used, the accuracy in simulating the meteorological conditions, as well as the graphic interface. Besides the controller's behavior, observations have been made regarding the human- machine interference and the robustness of the system. In all cases, the simulations have been performed in real-time and in manual mode, using a similar method as the one the pilot will use during the flight test.

The results and observations achieved from the simulations indicate a correct behavior of the controller. The time accuracy at the control waypoint is small enough to fulfill the operational requirements from a controller point of view. The use of thrust and speedbrakes has been acceptable within the scenarios that included disturbances and null in the ones without any disturbance having observed certain differences depending on the simulation environment used. The advisories were sent by the 4D-at an acceptable rate without adding a high additional amount of workload to the pilot. These and other results are shown throughout this project.

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ACRONYMS AND ABBREVIATIONS

AFMS	Advanced Flight Management System
AHMI	Advanced Human Machine Interface
ATC	Air Traffic Control
ATM	Air Traffic Management
ATRA	Advanced Technology Research Aircraft
CAS	Calibrated Air Speed
CDO	Continuous Descent Operations
CTA	Control Time of Arrival
DLR	German Aerospace Center
EFB	Electronic Flight Bag
FAA	Federal Aviation Administration
FAF	Final Approach Fix
FCU	Flight Control Unit
FL	Flight Level
FMGCS	Flight Management and Guidance System
FMS	Flight Management System
GECO	Generic Experimental Cockpit
GRACE	Generic Research Advanced Cockpit Environment
HITL	Human in the Loop
ICAO	International Civil Aviation Organization
ITD	Integrated Technology Demonstrator
LNAV	Lateral Navigation
ND	Navigation Display
NextGen	Next Generation Air Traffic System
NLR	National Aerospace Laboratory
PFD	Primary Flight Display
PID	Proportional Integral Derivative
PoE	Path on Elevator
QPAC	Quality Park Aviation Center
RTA	Required Time of Arrival
RWY	Runway
SESAR	Single European Sky ATM Research
SGO	System for Green Operations
SID	Standard Instrument Departure
SoE	Speed on Elevator
STAR	Standard Arrival
TAS	True Airspeed
TEMO	Time and Energy Management Operations
THR	Threshold
TMA	Terminal Manoeuvring Areas
ToC	Top of Climb
ToD	Top of Descent
VNAV	Vertical Navigation

INTRODUCTION

Today, air transport is one of the main elements in the world's largest industry, tourism and travel. It is also growing fast and the forecast is that it will continue to do so, as the traffic is expected to double over the next ten years and quadruple by 2050 [1]. With this growth has come the increasing environmental impact, with noise impact around airports and air pollution being the most significant problems. To maintain high airspace and airport usage and yet to fulfill the environmental limitations, various measures have to be taken.

At an operational level, within the current Air Traffic Management (ATM) structure, Continuous Descent Operations (CDOs) are performed at several airports during low traffic periods. This concept of operation allows the aircraft to descend continuously from cruise to landing with engines at or near idle while decreasing the levels of emissions and noise around airports. Despite the benefits provided by the CDO, nowadays its implementation is restricted to intervals of low traffic demand as larger separation between aircraft is needed. The additional separation required is a consequence of the limitation of the controllers to give radar vectors to traffic performing a CDO, as any change in speed or altitude will cause the interruption of the idle descent. One solution to the current limitation is a time managed CDO [2] [3] [4]. As already described within the Single European Sky ATM Research (SESAR) in the Initial 4D Trajectory Management Concept, introducing time as an additional variable to control an aircraft's trajectory is one of the goals of the future ATM network.

As part of the European research programme Clean Sky, two flight tests are foreseen and meant to prove the capability of performing an accurate time-managed CDO; one performed by the National Aerospace Laboratory (NLR) and one performed by the German Aerospace Center (DLR). Within this project, the flight test performed by the DLR at the Braunschweig airport is assessed. More specifically, the validation and preparation of a 4D-Controller that will enable the time constrained CDO is this project's scope.

The methodology used to assess the behaviour of the 4D-Controller is through simulations of the descent in different simulation environments. The first set of simulations are performed through the X-Plane v.10 simulator whereas the second set of simulations use a DLR developed simulator, the ATRA pre-flight testbed.

Following a logical order, the project is divided in four main parts. First, an introduction to the fundamental concepts of CDOs, time and energy management and a description of the 4D-Controller is shown. Next, the real flight test is described. Information regarding the experimental aircraft, the airport and the human machine interface (HMI) that will be used is presented. The prepared lateral trajectory that the aircraft will follow during the flight test as well as the altitude and speed profiles with their corresponding operational constraints are also present.

As two different simulation environments are used to asses the behaviour of the 4D-Controller, the third and fourth section of the project describe the methods used and the results of each simulation environment. Simulations with X-Plane are shown in the third chapter, whereas the use of the pre-flight DLR simulator is shown and analysed in the fourth chapter. The issues found with both simulation environments and the possible solutions and improvements to be made are included at the end of each section. Finally, the results and main conclusions of the project are shown.

CHAPTER 1. FUNDAMENTALS

1.1. CDO Concept of Operations

Increasing worldwide air travel has overloaded the current Air Traffic Management (ATM) infrastructure and caused the congestion of some airports. At the same time the environmental impact is nowadays an increasing problem and is becoming a limiting factor for the air transport stakeholders. To support further growth within the current regulations, less environmental footprint has to be achieved by the future air traffic.

Both the Single European Sky ATM Research SESAR [5] and the U.S. Next Generation Air Traffic System (NextGen) [6] have already described the existing problems and have identified the need of research and further development of new technologies and aircraft operations that could enable an efficient use of the available capacity of the airspace. The main goal is to develop and implement new technologies both airborne and ground based that would cope with the requirements regarding safety, capacity and environmental impact.

More environmentally friendly designs of engines [7] are being developed that ensure a decrease in the fuel consumption as well as less noisy aircraft. A lot of research is also being done in the field of composite materials that could decrease the weight of the aircraft and in that way reduce the amount of fuel needed [8].

Despite the numerous progresses that are being made, all the above mentioned technologies cannot be implemented through retrofit, only the new manufactured aircraft would benefit from them. Thus, the implementation of Continuous Descent Operations (CDOs) is a good alternative as the improvements are made in the operational field whose implementation has no dependency with the improvements made in the structure or engine part of the aircraft. The benefits of flying a continuous descent will be similar for a new improved aircraft as for an older one.

Knowing that the previously mentioned issues are particularly relevant in the terminal manoeuvring areas (TMA) surrounding the airports, in this context, CDOs offer an alternative to the usual step down approaches.

Today, air traffic controllers use speed and altitude instructions to separate the approaching and departing flow, causing the need of a level segment for an extended period of time. This level segment in some occasions is performed at a low altitude causing noise problems and the need of constantly burning fuel and generating gaseous emissions. In addition, the current procedure does not adjusts to the optimal behaviour characteristic for each aircraft, resulting in a more standard operation that does not optimize each aircraft's resources and performance capabilities.

As defined by the International Civil Aviation Organization (ICAO) [9] a CDO is *An aircraft operating technique aided by appropriate airspace and procedure design and appropriate air traffic control (ATC) clearances enabling the execution of a flight profile optimized to the operating capability of the aircraft, with low engine thrust settings and, where possible, a low drag configuration, thereby reducing fuel burn and emissions during descent"*. The shape of the vertical profile follows a continuous descent path that maintains the airplane at higher altitudes than the stepped-down approach and as a result, decreases the noise pollution in the airports nearby. Fuel consumption is also reduced as a consequence of the low thrust setting (ideally on idle) as well as the emission of contaminants. More exhaustive studies on the beneficial effects of the CDOs on the environment have been carried out as explained in [10] [11] [12] [13].

1.1.1. CDO descent profile

Current CDO profiles are calculated through the Vertical Navigation (VNAV) function of the existing Flight Management Systems (FMS). The descent profile is calculated backwards from the runway threshold towards the Top of Descent (ToD), taking into account all the known constraints, which can be altitude or speed constraints. The path connecting the constraints can be:

- **Performance path:** defines an idle descent from the ToD to the first constrained waypoint
- **Geometric path:**defines a path between two constrained waypoints or in such a way that it follows a prescribed vertical angle. The aircraft's elevator is used to control this type of path and thrust inputs are often needed to maintain speed. The use of the elevator to control the path is commonly known as Path-on-Elevator (PoE)

The CDO profiles are usually tailored to a specific airport needs and airspace organization based on the following considerations:

- CDO is available from ToD to a limitation, such as a hold/fix, airspace boundary, level restriction, etc.
- A continuously descending path is performed with a minimum of level flight segments only as needed to decelerate and configure the aircraft or to establish on a landing guidance system
- Variable descent gradients can be used depending on the specific characteristics of each aircraft (weight,speed, etc.)
- CDO profiles should be achievable for all aircraft types and flight conditions

A schematic view of the differences between a CDO vertical profile and a conventional step-down descent is shown in Figure 1.1.

Within the current ATM network, CDOs have been already implemented in several airports (Find progress implementation map in [15]). Nevertheless, a separation issue has derived from the fact that controllers are now restricted when giving radar vectors, as any change in the speed or altitude of the aircraft performing the CDO, will cause the interruption of the continuous decent with idle thrust. As a consequence, the introduction of larger separation (either of time or distance) is needed such that the CDO can be performed without ATC interference. The additional separation reduces the runway throughput, and as a result a decrease in the capacity of the airport arises. Therefore, CDOs are currently limited to hours of low traffic demand when larger separation can be added without limiting the airport's capacity.

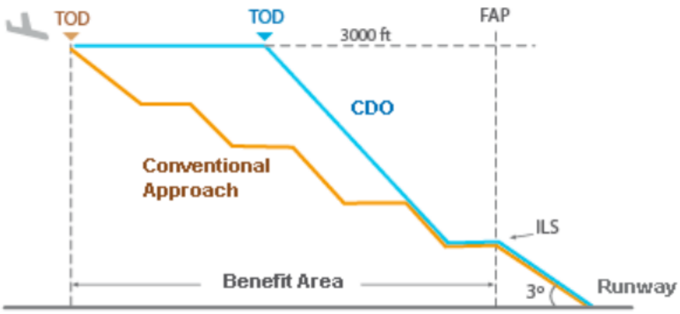


Figure 1.1: Vertical profile of a conventional step-down descent and a CDO. Source:[14]

Several technologies have been proposed to enable a better separation method meant to enhance the use of CDOs as explained in [16].

All these proposals actively adjust the speed profile through thrust inputs. These thrust variations will undeniably affect the levels of noise and contamination caused by the descent.

1.2. Time and Energy Management

Time managed CDOs in a future ATM network with improved capabilities would enable an extended use of continuous descents when compared with the present situation. Such a concept is already mentioned in the Initial 4D Trajectory Management Concept [17], part of SESAR that uses a time enhanced Control Time of Arrival (CTA) to achieve accurate time control at a single waypoint.

Having as a starting point this 4D ATM concept, a 4D CDO is developed by the European Programme Clean Sky up to a readiness level of 5.

Clean Sky is an ambitious aeronautical research programme composed of the European Commission and the european aeronautical industry, which aims at reducing the environmental impact of aviation, resulting in less noisy and more fuel efficient aircraft. Part of Clean Sky is the System for Green Operations (SGO) Integrated Technology Demonstrator (ITD) that among others, looks for tools that optimize aircraft trajectories.

As part of the SGO, a novel descent procedure that reduces environmental impact of aircraft is developed [16] and tested by the German Aerospace Center (DLR) [18] and the National Aerospace Laboratory (NLR) [19].

Throughout this project, a time and energy management procedure it is used as seen in [20]. Instead of acting directly on the engines throttles to control speed, a speed-on-elevator (SoE) command is used.

To have a better understanding on how this time and energy management is achieved by means of elevator deflections, the energy equations are presented below.

As the law of conservation of energy states, within a system, the total amount of energy remains constant over time. Moreover, it is known that energy can only change its form as it cannot be created nor destroyed. Assuming the aircraft as an conservative system, we can formulate that its total energy is the sum of its potential energy and its kinetic energy:

$$E_{tot} = \frac{1}{2}mV^2 + mgh \tag{1.1}$$

where m is the mass of the aircraft, h is the altitude above a reference frame, V is the aircraft's speed and g is the gravitational acceleration.

Examining this formula, it can be seen that an aircraft with a constant amount of E_{tot} can only interchange its potential energy (altitude) with its kinetic energy (speed). For an open descent, this translates into a speed reduction resulting in a higher altitude and a speed increase, in a lower altitude respectively.

On the other hand, if the aim is to change the aircraft's total energy the external forces capable of achieving that should be analysed. The only external forces acting on the aircraft in the longitudinal axis are the engine's thrust and the aerodynamic drag.

By differentiating Eq:1.1, the energy rate is obtained:

$$\dot{E}_{tot} = mV\dot{V} + mg\dot{h} \tag{1.2}$$

From the flight mechanics equations projected into the air reference frame the following equations are obtained:

$$\dot{V} = \frac{T - D - mg\sin(\gamma)}{m} \tag{1.3}$$

$$\dot{h} = V\sin(\gamma) \tag{1.4}$$

where γ is the flight path angle.

By substituting these expressions into Eq: 1.2 we obtain:

$$\begin{aligned} \dot{E}_{tot} &= mV\left(\frac{T - D - mg\sin(\gamma)}{m}\right) + mgV\sin(\gamma) \\ &= V(T - D) \end{aligned} \tag{1.5}$$

To modify the total energy rate, thrust and drag have to be modified. A change in the value of these parameters can be produced as:

- Thrust: act on the engine throttle
- Drag: command speed-brakes, deploy flaps or lower gear

With these restrictions in controllability, an accurate descent planning is needed for the 4D-CDO. To achieve the accuracy needed during descent, the aircraft performance model and weather forecasts are taken into account. The predicted trajectory is then computed and the position of the ToD is known such that the aircraft satisfies all time constraints.

Nevertheless, disturbances such as wind estimation errors or modelling errors can cause the aircraft to deviate in time or altitude once passed the ToD. If these disturbances do take place, and a difference between the predicted environment and the real one exists, several options for time management to satisfy the time constraint exist:

1. **Re-planning:** fly as planned and whenever time or altitude (or the equivalent energy) deviations overpass a certain boundary, a new 4D trajectory is generated. If no energy neutral solution exists, e.g. idle descent in clean configuration, thrust or speed-brakes will be added during planning. The frequency of re-plans is determined by the previously established time boundary.
2. **Control time over speed with Re-planning:** Time deviation is controlled by means of speed commands. This will shift all the errors in an altitude deviation that will trigger a new 4D trajectory generation when a certain boundary is crossed. Again, thrust or speed-brakes inputs are used during re-planning required.
3. **Control time and altitude** Similarly, time deviations are minimized by controlling speed. The resulting altitude error will be compensated if it overpasses a certain boundary. If this occurs, the aircraft is guided back to its initial trajectory by means of thrust or speed-brakes inputs. A trajectory regeneration is not required.

1.3. Clean Sky flight trials

Within the Clean Sky European project, a first step to prove the capability of flying a time constrained CDO with high accuracy was made by performing real-time simulation tests. Experienced pilots flew the previously prepared scenarios [19] [18] in both NLR's Generic Research Aircraft Cockpit Environment (GRACE) simulator and the DLR's Generic Experimental Cockpit (GECO) simulator. Both simulation tests gave satisfying results as most of the objectives initially set had been fulfilled [21] [22]. Additional simulation experiments have been conducted recently as to improve and update the current software [23] [24].These real-time simulations represent a first step towards the foreseen flight trials.

The next step to validate this novel procedure is by performing real flight tests testing the capability to fulfil a time constraint in a waypoint while descending with idle thrust settings. Within the Clean Sky European project, the following flight test are scheduled:

a) A fully automated 4D-CDO with a Cessna flight test aircraft (NLR)

This approach uses an experimental FMS on-board the flight test aircraft provided with an optimization algorithm to calculate energy-neutral trajectories and an improved guidance function to fly these trajectories. An idle descent with one time constraint is enabled by this system called TEMO (Time and Energy Management Operation). This 4D-trajectory will be flown by the flight control system using SoE. The trajectory will be flown as planned, following the first time management option described in the previous chapter. Initially an energy-neutral trajectory will be searched for by the on-board optimizer by managing all speed phases. If none is found, thrust or speed-brakes will be used additionally during the optimization.

b) A ”manually” flown 4D-CDO with an Airbus A320 flight test aircraft (DLR)

A set of advisories are given on an iPad which the pilot then introduce into the Flight Control Unit (FCU). The iPad is certified as a second class EFB (Electronic Flight Bag) (further information is given in the next chapter). A 4D-controller calculates the given advisories based on the initial 4D-trajectory speeds to be flown. The 3rd time management option mentioned in the previous chapter is used. (See Control time and altitude in previous chapter). Advisories to use speed-brakes or vertical speed, resulting in thrust application will be displayed on the iPad whenever the altitude deviation is higher than 1000 ft. This approach uses no regeneration of the initial 4D-trajectory. The aircraft will be flown in open descent, using SOE and thrust setting on idle. The initial 4D-trajectory for time constrained CDO is calculated by the DLR's experimental FMS, the Advanced Flight Management System (AFMS).

This concept of use works for all 4D-trajectories. Nevertheless, in this case we focus on a time constrained CDO 4D-trajectory.

1.4. 4D Controller

Within this project, a novel, closed-loop 4D-Controller developed by the DLR is used to handle time deviation.

The controller used is a Proportional-Integral-Derivative controller (PID controller), that minimizes the time error by using a control loop feedback mechanism. Besides the usual proportional, integrative and derivative constant parameters, the controller's algorithm includes a filter to avoid frequent speed changes.

The 4D-Controller controls time by modifying the CAS of the aircraft. The action of detecting and correcting time deviations is constantly done by the controller.

As a consequence of the speed management through elevator deflection, an exchange of energy between kinetic energy and potential energy takes place. Thus, every time the controller commands a $\triangle$CAS, an altitude deviation relative to the initial altitude profile occurs. The altitude deviation, contrary to time deviation, has deviation boundaries to fulfil ($\pm$1000 ft). Whenever the boundaries are crossed, speed-brake or thrust inputs are commanded depending on the aircraft's position relative to the initial altitude profile. Speed-brakes are applied whenever the aircraft is higher than the planned altitude e.g. speed reduction, whereas thrust is added when the aircraft is lower than the planned altitude, e.g. speed increase.

A similar concept has been developed by Boeing that also combines the use of the elevator (SoE) and throttles to achieve an accurate 4D-trajectory of a time constrained CDO [25]. To handle time deviations, ground-speed advisories are given in this case. As also claimed by the Boeing approach, one of the benefits of using a 4D-Controller to handle time deviations is that an enhanced predictability of the trajectory is achieved. This factor represents a big advantage for future Air Transportation System.

2.1. The experimental aircraft

The aircraft that will be used during the flight test is the Airbus A320-232 ”D-ATRA” (Advanced Technology Research Aircraft) available at the DLR. Apart from its size, this modern flight test platform has several modifications that enables the ATRA to different fields of research such as aerolastic measurements techniques, space acoustic, measurement of turbulence, etc. Moreover, the ATRA has several cockpit interfaces that allow the investigation in other research fields such as pilot workload and flight control commands in the field of autonomous flight, pilot assistance and display technology. [26]


Figure 2.1: Airbus A320 ATRA Source:[26]

A brief description of the technical data of the aircraft is available below.

Technical data	Airbus A320 ”D-ATRA”
Length	37.57 m
Height	11.76 m
Wingspan	34.10 m
Empty weight	42.3 t
Total weight	max. 75.5 t
Engines	two International Aero Engine V2500 engines
Thrust	111 KN/engine
Range	4800 km - 5700 km
Flight altitude	max. 11,800 m/ 39,000 ft
Speed	max. 840 km/h
Endurance	up to 2h 30m for test operation
Fuel tank capacity	23,858 l
DLR flight facility	Braunschweig

Table 2.1: Airbus A320 ”D-ATRA” Technical Data [26]

Regarding the A320 Autoflight System, the typical procedures are flown in managed automatic mode. This means that by only pushing the selector knobs on the FCU (Fig: 2.2) , the Autoflight System will follow the flight plan previously entered into the FMS by the pilot. On the other hand, if the pilot desires to take control over the speed, altitude, heading and vertical speed values, then the selected mode can be activated by simply pulling the selector knobs on the FCU. [27]

When it comes to current non-time managed CDO interfaces, the A320 FMS provides a continuous descent mode in the FMS, which calculates the trajectory from the runway to the ToD and then follows that trajectory in managed mode. Nowadays, this type of operation offer no information to the pilots concerning the CDO. Moreover, pilots have no

Figure 2.2: Airbus 320 FCU

control neither guidance on the CDO's path. If they choose to enter the selected mode, the descent will most probably stop being idle.

2.2. Human Machine Interface

In order to enable the managed mode while performing a CDO, 4D-Guidance information is given to the pilot. Ideally this information should be displayed in the already existing Navigation Display (ND) and Primary Flight Display (PFD) by speed cues on the speed bar or virtual waypoints on the ND. Nevertheless, this approach requires an exhaustive retrofit of the existing aircraft cockpits.

A different approach undertaken by the DLR suggests the use of an EFB to provide the required 4D-Guidance information to the pilot as the retrofit procedure would not be so complex. Electronic flight bags are nowadays used by pilots for several tasks. Depending on the EFB's class, the device is used to store in a more efficient way the maps and the mandatory documentation that have to be present in every cockpit (Class 1 EFB) or even to connect with the aircraft and display information from the aircraft's systems (Class 2 EFB). For our purpose, a Class 2 EFB is needed as the 4D-Guidance module needs constantly information from the aircraft's systems. In this case, an Apple iPad certified as a Class 2 EFB with an interface unit that connects the aircraft to the iPad is used. The additional interface unit is needed if we want to use the iPad as a Class 2 EFB. This interface connects with the aircraft through the ARINC data bus and with the iPad through short range radio communications. [28]

2.2.1. HMI functionalities

The main functionalities of the 4D-Guidance module are described below. The complete view of the different advisories displayed on the iPad is shown in Figure 2.5.

- **FCU advisories**

  In order to enable the time constrained CDO in selected mode, a guidance advisory based on the available knob selectors on the FCU is needed (Fig 2.3). The colors used (*amber and green*) represent whether the parameter displayed in the HMI corresponds with the one introduced by the pilot in the FCU (*green*) or not (*amber*).

  - CAS advisories: To fly a time accurately CDO and to obtain an idle descent through time and energy management as explained in previous chapters relies on the clever exchange of potential energy (altitude) and kinetic energy

Figure 2.3: CAS (kt), Altitude (ft), Heading (°) and Vertical Speed (ft/min) indications on the HMI

(speed). Therefore, to meet the time constraint, pilots need to select the recommended Calibrated Air Speed (CAS) calculated by the 4D-Controller shown on the HMI display. This will represent the most frequent task for the pilots. However it has to be reminded that this CAS values are only a recommendation for the pilots, and never a mandatory procedure. The reason behind the CAS changes that the pilot will seize are due to either deceleration phases from the initial speed profile or to time deviations caused by disturbances that will make the controller to send faster or slower speed commands. The CAS advisories are displayed every 5 kt. This means that a new CAS advisory is not displayed to the pilot if there is not a minimum increment of 5 kt between the old advisory and the new one.

- Altitude advisories: The pilot receives advice regarding the altitude selection whenever an altitude change exists in the initially computed altitude profile.
- Vertical speed advisories Whenever the aircraft is below the altitude profile and the altitude error exceeds the allowed boundary ($\pm$ 1000ft), thrust inputs are needed in order to fly an accurate vertical trajectory. A way to control the engine's thrust is through vertical speed. Therefore, a vertical speed recommendation is displayed on the HMI. Similarly, a *"Speed brake"* cue message is displayed when the aircraft is 1000 ft or more above the planned trajectory.
- Heading advisories The heading value is automatically introduced into the aircraft's FMS through the NAV lateral mode. Therefore, a dashed line appears below the heading label and no action is required from the pilot's side.

■ **Time and altitude errors**

Indications of the time and altitude errors are displayed on the HMI to offer the pilot details of the accuracy of the performed CDO (Fig.2.5 (1) and (2)). The time error displayed is simply the value obtained from the difference between the planned and current position along the trajectory. In a similar way, the altitude error is the difference between the planned and the current altitude. The allowed boundaries of the altitude error are also represented ($\pm$1000 ft understanding positive values as above the trajectory and negative values as below the trajectory).

Besides the informative purpose,this information enables the pilot to foresee the aircraft's behaviour and make a better use of the CAS recommendations.

■ **Configuration changes**

The deployment of flaps/slats and gear is displayed on the HMI. These indications are given through text cues as shown in Figure 2.5 (3) . Moreover, the current state of the gear and flaps position is also shown in a similar way to the exiting A320 displays. The configuration change advisories are taken directly from the computed trajectory. Their main objective is purely informative and there is no intention of trying to adjust the time error through an active control of the deployment of flaps and gear as done in other studies. [16].

- **Approach Mode**

  A text cue appears when the pilot has to engage the Approach mode (Fig.2.4). The Approach Mode arms the localizer and the glideslope autopilot modes. Once the Approach Mode is armed the 4D-Guidance stops and the pilot has to follow the usual final approach procedure. Once the Approach mode is engaged the HMI interface will start to show the planned values of speed, altitude and no longer give advisories to adjust the time error. As previously explained, information regarding the configuration changes is still given however it has no effect on the time error.

APPROACH MODE

Figure 2.4: Approach Mode Advisory

Figure 2.5: iPad Display

As seen on the iPad display, a navigational display (Fig. 2.5 (4)) similar to the one in the main instrumentation of the A320 is showed. The ToD and the moment of configuration change is indicated along the trajectory in order to increase the pilot's awareness.

2.3. Lateral Route

One of the first steps of the flight test preparation is the development of the lateral route that the aircraft has to follow during the real flight test. This route information will be the one implemented into the aircraft's FMS and the one used in further real-time simulations and analysis.

The flight test will be performed at the Braunschweig airport (EDVE). The main airport information is presented below.

Airport	Braunschweig-Wolfsburg		
ICAO Code	EDVE		
Elevation	297 ft	**Reference Temp.**	21.9 ° C
MAG Var	1.9° E	**Annual change**	2012,7

	True Bering	**TODA/LDA**	**THR Coordinates**
RWY 08	085°	2300 m/2000 m	N 52 19 07.178 E 010 32 47.358
RWY 26	265°	2300 m/2300 m	N 52 19 13.061 E 010 34 32.501

Table 2.2: Braunschweig (EDVE) Airport Information

Taking into account that the exact weather situation from the day of the flight test is currently unknown, the route that will be flown by the aircraft must be designed so that the aircraft can land and depart from both available runway directions. This means that whatever the wind direction is going to be in that specific day, both possibilities (depart from RWY08 or RWY26) will be prepared and assessed.

The flight experiment is restricted to the published arrival routes near the airport. At the EDVE airport, certified Standard Instrument Departure (SID) and Standard Arrival (STAR) are already available for flying CDOs. The following additional criteria has to be considered for the chosen departure route and en-route:

- The route has to be long enough to reach the Top of Climb (ToC)
- The route should avoid transited airspace areas
- The route should contain turns as the capability of the controller in curved trajectories is one of the factors that is going to be tested
- The route must contain a cruise segment in order to set up the experiment before the ToD

The following tables contain the waypoint list overflown by the aircraft satisfying the situation explained above for both RWY26 (Table 2.3.) and RWY08 (Table 2.3.).

<table>
<tr><th colspan="3">SID DLE6T RWY26</th></tr>
<tr><th>WP</th><th>Coordinates</th><th>Constraints</th></tr>
<tr><td>RWY26</td><td>N52 19 13.061 E010 34 32.501</td><td>-</td></tr>
<tr><td>LEINE</td><td>N52 15 01.15 E009 53 00.58</td><td>-</td></tr>
<tr><td>NIE</td><td>N52 15 01.15 E009 53 00.58</td><td>-</td></tr>
<tr><th colspan="3">STAR ABM1D RWY26</th></tr>
<tr><th>WP</th><th>Coordinates</th><th>Constraints</th></tr>
<tr><td>ABMAL</td><td>N53 26 31.45 E010 54 43.13</td><td>FL220$\leq$ alt $\geq$ FL150</td></tr>
<tr><td>VE454</td><td>N53 04 21.23 E010 54 13.73</td><td>FL150$\leq$ alt $\geq$ FL110</td></tr>
<tr><td>VE455</td><td>N52 39 40.40 E010 53 41.57</td><td>alt$\geq$FL70</td></tr>
<tr><td>VE458</td><td>N52 23 35.47 E010 53 20.95</td><td>-</td></tr>
<tr><td>VE028</td><td>N52 20 03.12 E010 49 47.50</td><td>Max IAS 220kt</td></tr>
<tr><td>LIDMO</td><td>N52 19 41.15 E010 43 01.31</td><td>alt$\geq$2000 ft</td></tr>
<tr><td>RWY26</td><td>N52 19 13.061 E010 34 32.501</td><td>-</td></tr>
</table>

Table 2.3: RWY26 SID and STAR waypoint information

<table>
<tr><th colspan="3">SID BATEL5U RWY08</th></tr>
<tr><th>WP</th><th>Coordinates</th><th>Constraints</th></tr>
<tr><td>RWY08</td><td>N52 19 07.18 E010 32 47.36</td><td>-</td></tr>
<tr><td>HLZ</td><td>N52 21 48.22 E010 47 42.79</td><td>-</td></tr>
<tr><td>BATEL</td><td>N52 32 49 E011 05 59</td><td>-</td></tr>
<tr><th colspan="3">STAR ABM1C RWY08</th></tr>
<tr><th>WP</th><th>Coordinates</th><th>Constraints</th></tr>
<tr><td>ABMAL</td><td>N53 26 31.45 E010 54 43.13</td><td>FL240$\leq$ alt $\geq$ FL170</td></tr>
<tr><td>VE406</td><td>N53 00 28.90 E010 38 58.99</td><td>FL150$\leq$ alt $\geq$ FL110</td></tr>
<tr><td>VE407</td><td>N52 38 41.72 E010 26 04.46</td><td>alt$\geq$ FL70</td></tr>
<tr><td>VE405</td><td>N52 23 13.85 E010 16 58.50</td><td>-</td></tr>
<tr><td>VE013</td><td>N52 18 15.61 E010 17 44.78</td><td>Max IAS 220kt</td></tr>
<tr><td>MAGER</td><td>N52 18 38.10 E010 24 14.29</td><td>alt$\geq$2000 ft</td></tr>
<tr><td>RWY08</td><td>N52 19 07.18 E010 32 47.36</td><td>-</td></tr>
</table>

Table 2.4: RWY08 SID and STAR waypoint information

The STAR charts for both RWY08 (Fig: 2.6) and RWY26 (Fig: 2.7) are shown below. The corresponding SID and Approach charts for each runway can be found in Appendix A.

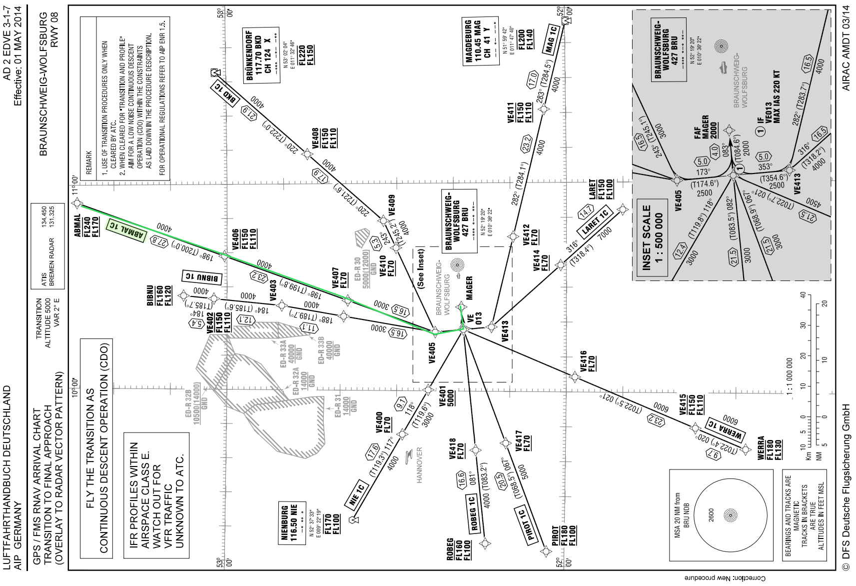


Figure 2.6: STAR Runway 08

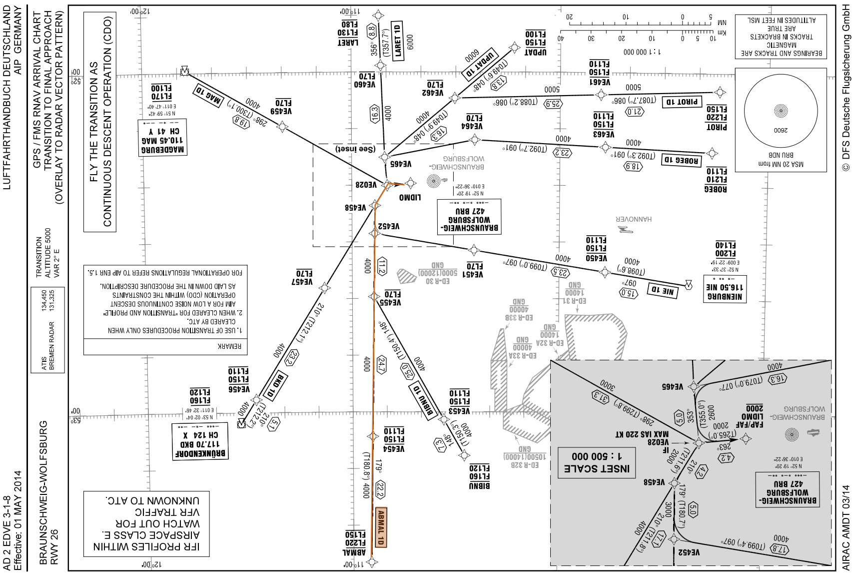


Figure 2.7: STAR Runway 26

2.4. Speed and vertical profile

Regarding the speed and vertical profile of the route, an initial planning must be done taking into account the operational restrictions of the aircraft as well as ATC restrictions given in the appropriate charts for SID's and STAR's. During the flight test, the FMS will query for the aircraft performance database when generating the trajectory. Speed and altitude constraints originating from the ATC are also available in the on-board NAV database.

The list of the main A320 operational and performance restrictions that have been taken into account can be found in Annex B.

The initial speed and altitude profiles for the approach towards the RWY08 and RWY26 are represented in the Fig: 2.8 and Fig: 2.9.

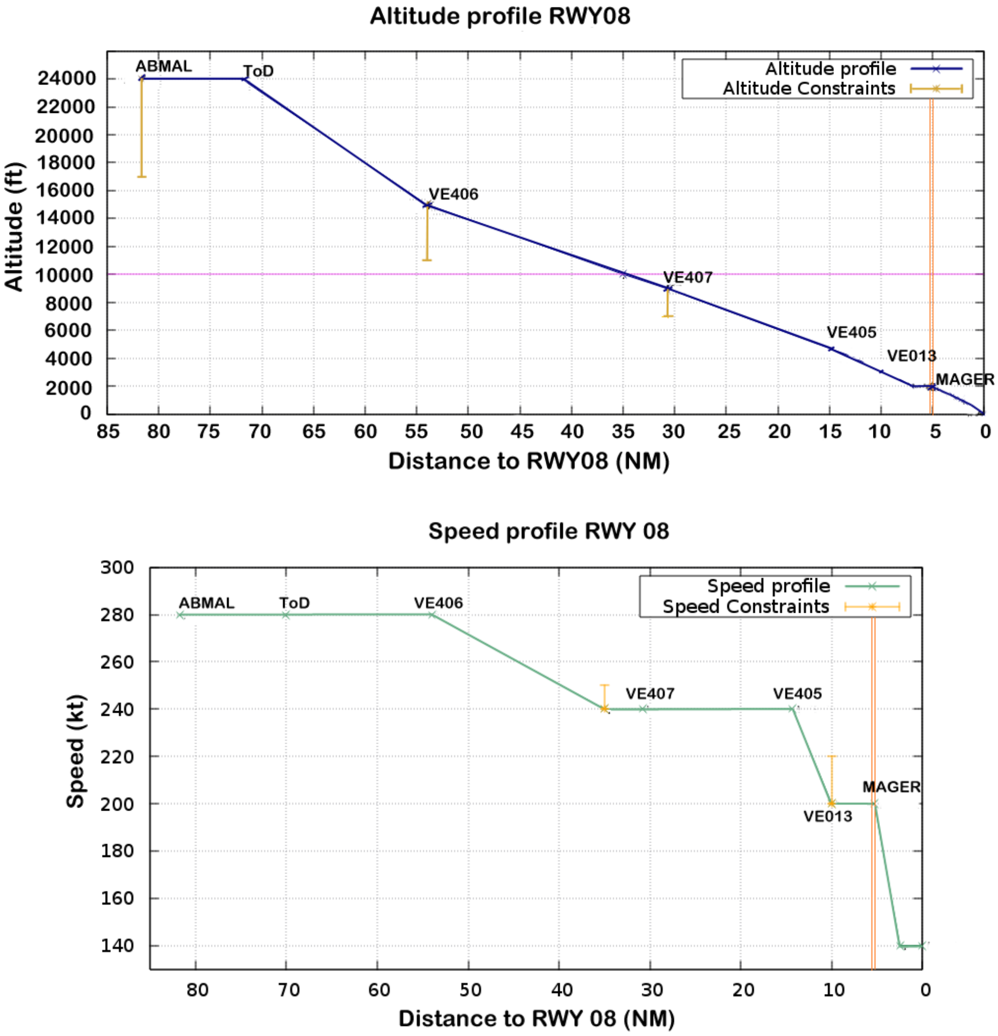


Figure 2.8: Altitude and Speed profile RWY08

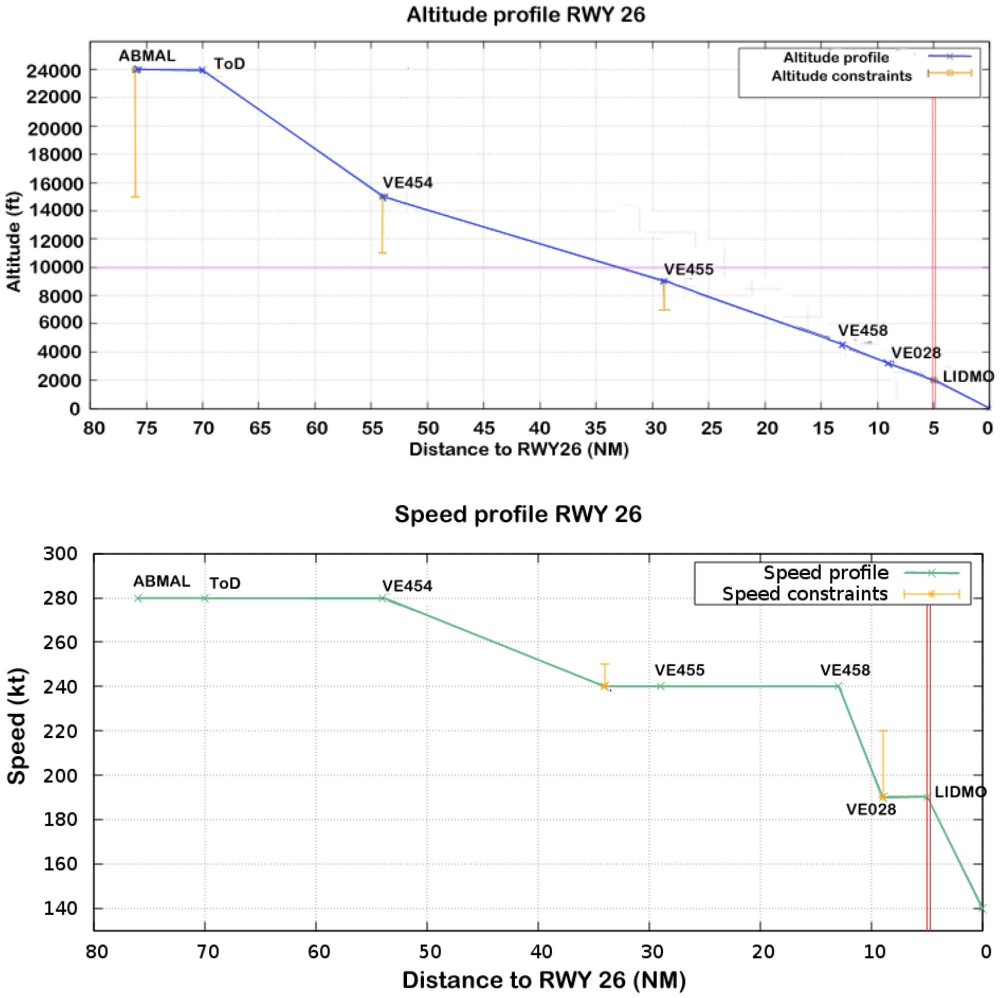


Figure 2.9: Altitude and Speed profile RWY26

As we can see, the initial profiles give us a simple view of the aircraft's behaviour in terms of speed and altitude as well as information related with the constraints and in which part of the trajectory they apply.

The cruise altitude has been set to 24 000 ft based on past experiments performed at the EDVE airport. This cruise altitude is not in line with the ABMAL upper restriction when performing the descent towards the RWY26 (See Table 2.3.). Nonetheless, taking into account that the airport has a low traffic density it has been decided to keep this value for this particular study. The actual trajectory flown will also have to take into account the pilot's opinions from their previous experience.

After the cruising phase, the descent is started at the ToD. It has to be highlighted that both the position of the ToD and the descent angle are schematically represented in the graphs and the real vertical trajectory will be calculated by the FMS prior to the controller initialization. Once the controller is engaged, these trajectories will be adapted in order to minimize the time error at the constrained waypoint.

Regarding the speed profile, a constant CAS phase is initially flown Then a deceleration to 240 kt is needed in order to fulfil the speed restriction at FL100. A second decelerating phase is performed just before the glideslope interception where the aircraft reduces the speed to be able to execute the approach.

The vertical red lines indicate that the guidance is no longer available and that the pilot must follow the normal final approach procedure. The guidance disconnects once the Approach mode is selected. In the above graphics this point is taken at the final approach fix (FAP).

A graphic indication (Fig: 2.10) of the moment when the flaps/slats configuration and gear position should change is computed with the purpose of being compared with the actual controller indications. An approximation of the speed at which this configuration change should take place taking into account the operational limits is showed.

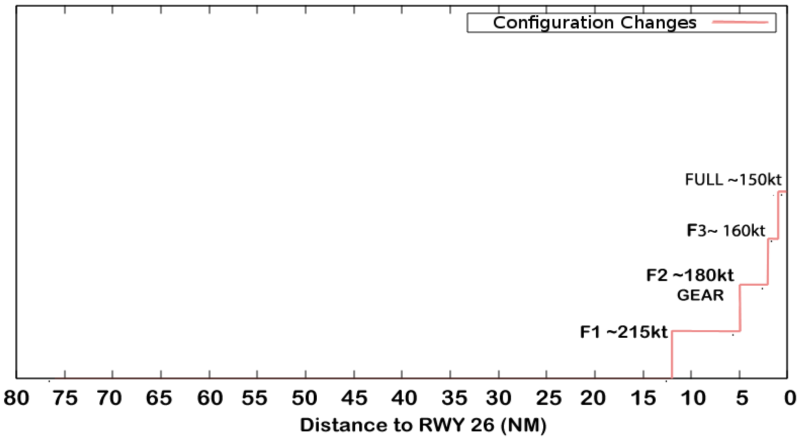


Figure 2.10: Configuration changes

CHAPTER 3. FIRST SIMULATION ENVIRONMENT (X-PLANE)

The main purpose of this project is to evaluate and analyse the behaviour of a 4D controller during a continuous descent operation. The first simulation environment has as a main feature a realistic cockpit of the aircraft that will be used during the real flight experiment. Therefore the assessment of quite realistic issues that the pilot could encounter on board of the aircraft is achieved.

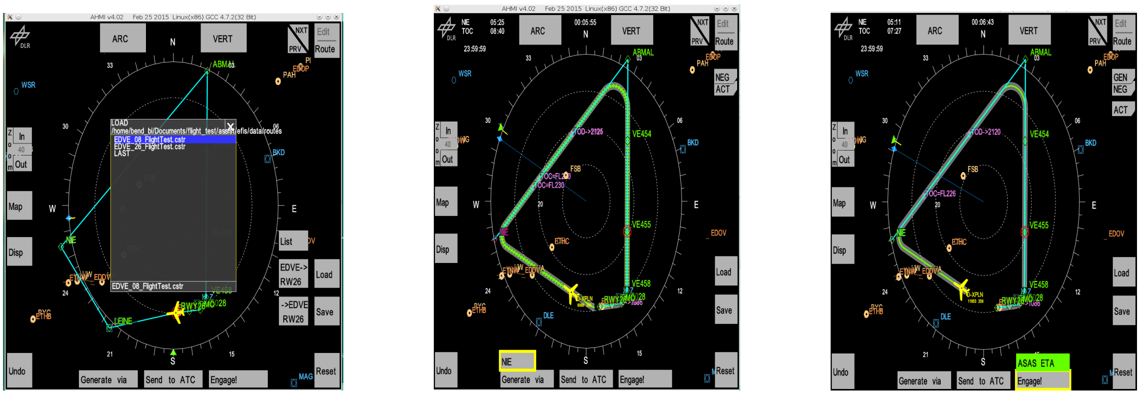
3.1. Simulation software

The flight simulator used is X-Plane v.10 [29], a FAA-certified software from Laminar Research. This flight simulator provides us with very realistic graphic interface and accurate airport information. A weather model is also present and different atmospheric conditions can be simulated. Regarding the aircraft, a highly detailed model of the A320 is being used, including avionics systems, flight management and guidance system (FMGCS) as well as hydraulic and electric bus systems. This improved model is provided by the Quality Park Aviation Center (QPAC) company. An example of the X-Plane graphical interface is shown in Fig: 3.1.

Figure 3.1: X-Plane A320 Cockpit

Besides the X-Plane graphical interface, additional tools are used to have a better understanding of the aircraft's behaviour and the controller's performance. A short list and explanation of all of them is available below.

- **Advanced Human Machine Interface (AHMI):** This display shows the lateral route of the aircraft in a more detailed way when compared with the aircraft's ND. Information related with the nearby waypoints, navigation aids, airports is available as well as the position of the ToC and ToD. The route waypoints and constraints are loaded through this interface Fig: 3.2(a). Additionally, the route negotiation with the ATC and its corresponding activation is also done by means of the AHMI Fig: 3.2(b) and Fig: 3.2(c). Forcing a re-plan or creating a route directly to a WP is also possible and enabled by the software.



(a) Insert waypoints and constraint list

(b) Generate a route direct to NIE waypoint WP

(c) Engage the selected route

Figure 3.2: AHMI functions

- **FMS Trajectory:**This additional software created by the DLR gives us an improved view of the aircraft's altitude, speed, thrust profile (Fig: 3.3) and other characteristics of the aircraft. Moreover, a real-time graph is also displayed indicating the time and altitude error of the aircraft at every moment. The route constraints are taken into account and displayed along the profiles as for example the speed restriction at the FAP LIDMO.

  The different colors represent different sub-phases of the flight that have been used while planning the initial altitude and CAS profile. For example the green segment indicates a constant altitude while decreasing the CAS phase. Once the simulation begins, the actually flown profile will be represented in red. (See Fig:3.5).

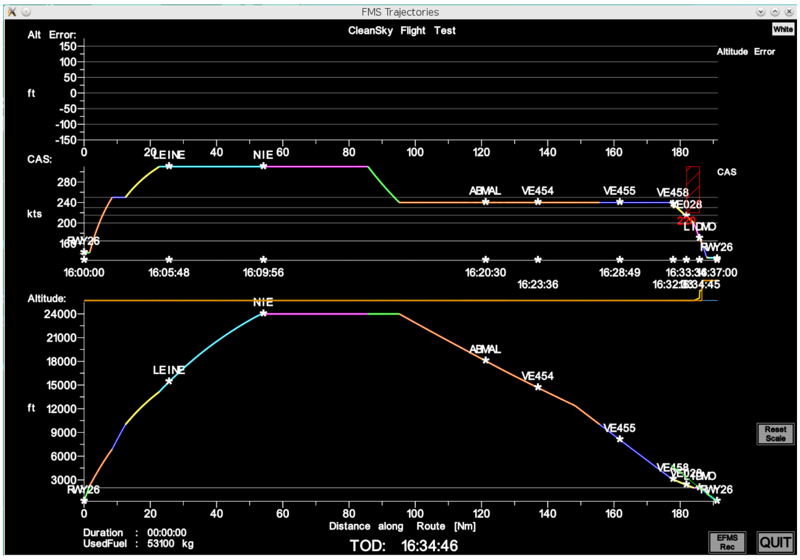


Figure 3.3: Initially planned altitude and speed profile

- **Controller interface:** Being this a computer simulation, the HMI display that would be on the EFB is here represented by a simple display containing data and information related with the internal parameters of the controller and the current aircraft state.The commanded values of speed and altitude, vertical speed, and heading are also showed as these will have to be introduced into the aircraft's FCU. Moreover, a numeric indication of the time and altitude errors is displayed.

3.2. Assumptions

In this first simulation environment a series of assumptions have been considered:

1. Aircraft performance is subjected to X-Plane modeling algorithms and therefore differences between the real aircraft behaviour and the simulated one can appear.
2. The weather conditions simulated contain only wind speed and direction values set at discrete altitude points following X-Plane's modelling pattern.
3. No wind is taken into account into the FMS when the initial trajectory is computed.
4. The speed and altitude profile followed are the ones computed by the aircraft's FMS.
5. The heading is the only parameter that is set automatically and transmitted to the FMS. Therefore heading is flown in managed mode and as a consequence pilot workload is reduced a lot .
6. The rest of the parameters are introduced manually into the simulated FCU. Therefore,delays regarding the input of the commanded values might be present as in the real flight test.
7. The descent is the only part of interest to validate the 4D-Controller and the new CDO procedure. Nonetheless, the simulations are performed including take-off, climb and cruise in order to get different starting conditions and to test the initialisation of the controller.

3.3. Definition of scenarios

In order to isolate causality within the model, several independent variables have been selected:

- **Independent Variable 1:** Airport Runway (RWY26 vs. RWY08)
- **Independent Variable 2:** Initialisation condition (Early initialization vs. Late initialization).

  During the flight test the 4D controller will be engaged shortly before the ToD as the main focus is on the 4D-CDO. Prior to the 4D-Controller engagement, a trajectory generation is required to avoid big errors that could not be compensated by the controller in the available speed regime. The on-board AFMS allows the generation of a new trajectory in any phase of the flight. This gives the possibility to engage the 4D-Controller several times during one simulation run to test its initialization. Therefore, two different cases are simulated: an early initialization, while climbing and a late initialization, prior to the ToD. In this way, the simulations analysed include all the route (early initialization) or only the descent part of the route (late initialization).

- **Independent Variable 3:** Meteorology wind forecast errors (No wind / Constant headwind/ Constant tailwind/ Gusting headwind/ Gusting tailwind).

  Different wind conditions are simulated. In each case the initially planned trajectory takes no wind into account. Therefore, the wind simulated in this scenarios is considered by the system as a forecast error.

  As the weather interface of X-Plane allows us, wind direction and speed are set at different altitudes 2000 ft, 8000 ft and 18000 ft respectively. In the constant wind scenarios a 10 kt wind speed is simulated. The gusting wind is achieved by varying a maximum of 3 kt around the 10 kt value. The direction of the wind is selected so that a headwind and tailwind component is encountered along the descent. During the rest of the trajectory there is no headwind or tailwind purely component.

The scenarios tested in this first simulation environment include a combination of all these independent variables. The following table describes the simulated scenarios.

	Guidance	Initialization cond.	Wind cond.
RWY26	HITL	Early	No wind
	HITL	Late	No wind
	HITL	Late	Constant wind (Headwind and Tailwind)
	HITL	Late	Gusting wind (Headwind and Tailwind)
RWY08	HITL	Early	No wind
	HITL	Late	No wind
	HITL	Late	Constant wind (Headwind and Tailwind)
	HITL	Late	Gusting wind (Headwind and Tailwind)

Regarding the guidance mode, two different options are enabled by the system. We can distinguish between the simulations where the input of speed, altitude and vertical speed advisories is done manually, human in the loop (HITL) or when all these commands are sent directly from the controller to the aircraft's FMS (automatic mode). Within this project, the first option is considered. Manual inputs of the controller's advisories offer a more realistic simulation as the real flight test will be performed in the same way.

3.4. Discussion of results

In this section, the behaviour of the controller is analysed and discussed from the corresponding time, altitude and speed graphics obtained from the simulations. Numbers have been used to mark into the graphs the controller's answer to the different simulated scenarios. Observations made during each real-time simulation are also exposed.

The graphical data obtained from each scenario simulated can be found in the Appendix B.

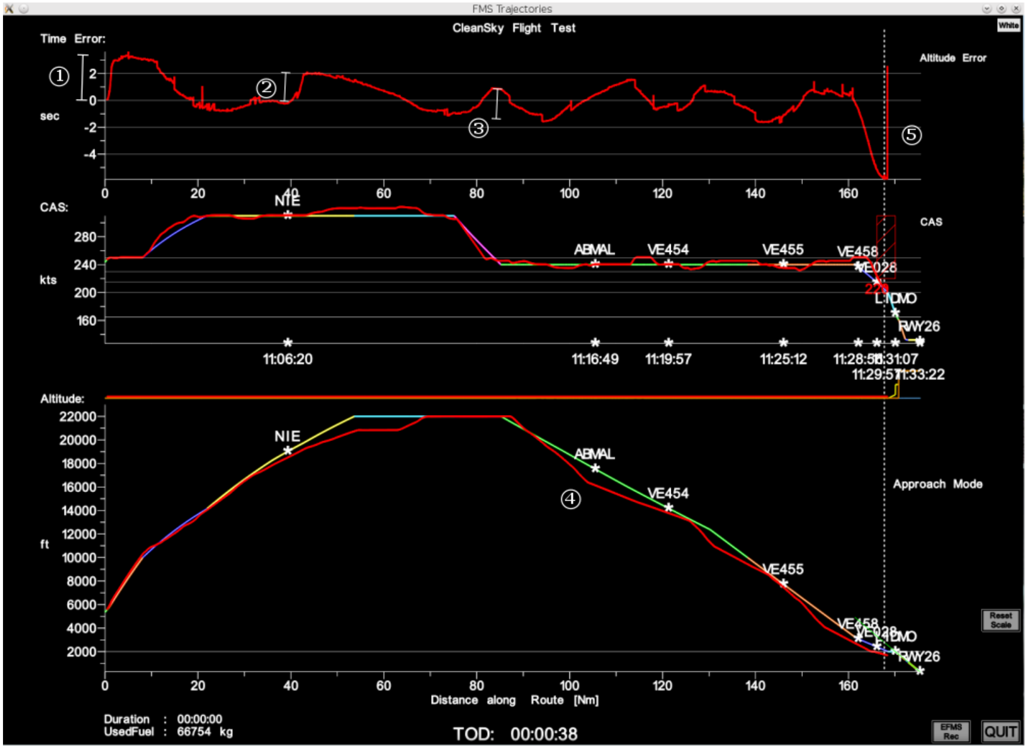
3.4.1. Initial trials

Although the scenarios previously mentioned are the main ones discussed and analysed along this section, it must be highlighted that some previous simulations have been performed. These simulation runs had as an objective the initial assessment of the interaction between the X-Plane environment and the controller interface. Moreover, the lateral guidance advisory given by the controller is manually introduced in these particular runs. A list of the observations made during these pre-runs is presented below.

- **Initialization:** It is observed that there is a need for a controller reset each time a new initialization is performed. This occurs after the trajectory generation. If for any reason during the simulation (or later on during the flight test) a new 4D-trajectory is generated, the 4D-Controller must be first disengaged and manually restarted. On the contrary, as observed during the initial simulations the guidance advisories are not coherent nor effective for the achievement of the CDO.
- **Turns:** The time error increases (goes into the late area) when the aircraft is performing a turn. The magnitude of the error is bigger when the lateral guidance is not in automatic mode NAV but manually introduced by the pilot.
  - The performance of the turns is going to be further analysed and discussed in the next sections as it represents one of the objectives to be tested on the controller.

3.4.2. Baseline. No-wind scenarios

Next, the very first scenarios containing no wind and no re-plans of both runways are analysed. These constitute the baseline for the following simulation runs.



Duration : 00:00:00
UsedFuel : 66754 kg

TOD: 00:00:38

Figure 3.4: RWY26 No wind and no re-plan simulation

From the different graphs in the figures 3.4 and 3.5 a series of observations have been made:

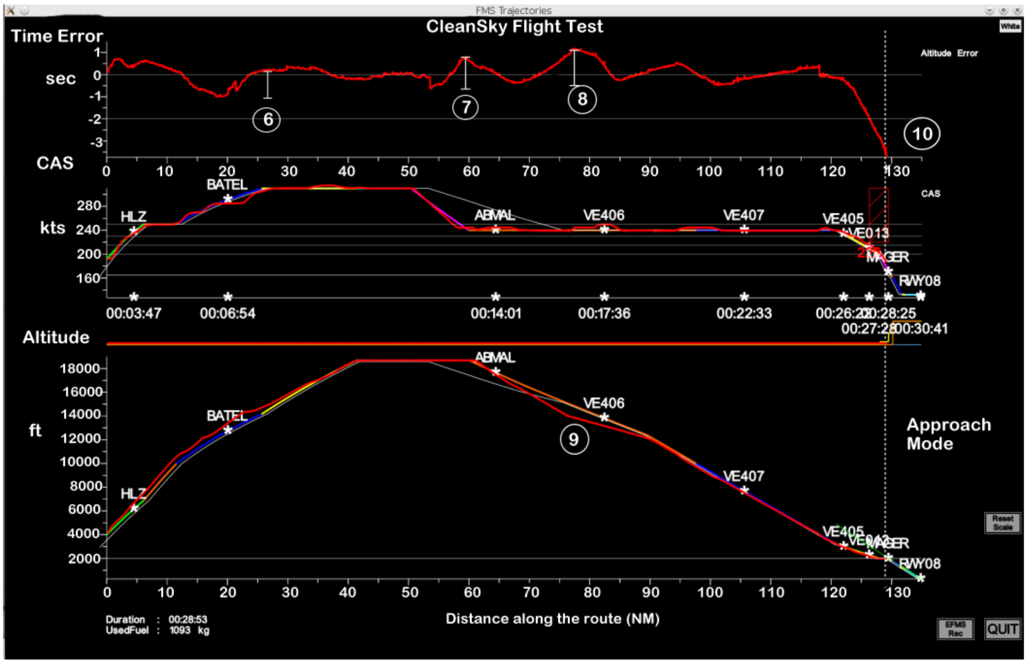


Figure 3.5: RWY08 No wind and no re-plan simulation

- Initially a jump in the time error **(1)** can be seen. As it has been observed in several simulation runs, this jump is caused by the fact that the initial trajectory is modified and shorten to fly directly towards the NIE waypoint. Thus, a turn is needed to go direct to NIE waypoint.

- A second jump in the time error of approximately 2 seconds can be seen as the aircraft executes the turn at NIE waypoint **(2)**. As a result, the speed is increased by the controller and therefore the aircraft is now below the initial altitude profile.

- It can be seen in **(3)** that due to the simple energy management concept, if the aircraft is decelerating while at constant altitude, the time error will go into the late area as expected.

- At the ToD, when the idle descent starts, the aircraft's vertical profile is steeper than initially planned, and therefore an input of vertical speed is sent by the controller in **(4)**. The vertical speed is maintained until the altitude error is less than 200 ft. This behaviour of steeper than planned vertical profile is repeated as we can see in the altitude profile graph. The X-Plane A320 model is not correct when compared to the ATRA, e.g. descends too steep, resulting in altitude errors even in no-wind situations. Descending steeper than planned causes the controller to command lower speeds. Less potential energy results in higher kinetic energy, thus the controller needs to advise lower speeds to compensate ans avoid arriving earlier.

- Whenever the X-Plane is paused, a sharp peak appears in the time error graph as seen in **(5)**. This has to be ignored as it is caused by the fact that X-Plane is not able to produce accurate timing in situations of high computer load. The same effect has been noticed when additional windows are opened on the computer screen.

- When analysing the RWY08, similar behaviour is observed. It can be seen in **(6)** that the turn in BATEL caused an increase in time error towards the late area. The same can be observed while turning at ABMAL waypoint **(8)**. This time error is larger in the latest waypoint.

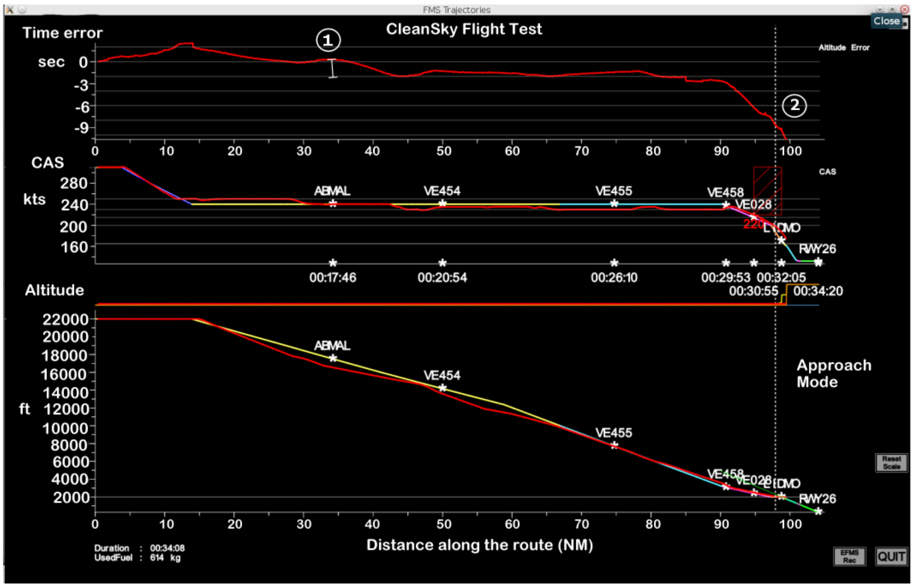
- Again in **(7)** an increase in time error is noticed due to the decelerating phase at constant altitude that the aircraft is performing.
- The steep descent that the aircraft is performing is observed in (9). In this particular situation, only one input of vertical speed was needed to correct the vertical path of the aircraft.
- Finally in **(10)** it can be seen that in no wind situation the tendency of the aircraft is to arrive earlier. The descent towards RWY26 resulted in a 6 seconds earlier arrival whereas the one towards RWY08 resulted in a 4 seconds earlier arrival.

3.4.3. Wind scenarios

When trying to analyse the wind scenarios, similar behaviours are detected. No significant changes have been found between the two runway directions. Therefore, in this section only the graphical data when simulating RWY26 scenarios is commented. The remain simulated scenarios data can be found in Annex C.

All the scenarios that include wind are analysed only in the descent part of the route (from the ToD), as the accumulative wind effect along the whole trajectory adds quite high time errors, that in reality will not exist as the purpose of the controller is to be engaged near the ToD and not earlier.

When analysing the differences between constant (Fig: 3.4.3.) and gusting tailwind (Fig: 3.4.3.), it can be seen that the time error originated at the ABMAL turn is higher **(1)**. Moreover, the final time deviation **(2)** just before disconnecting the guidance is also slightly bigger going up to 10 seconds earlier in the scenario with gusting wind and 9 seconds earlier in the scenario with constant wind.



Duration : 00:34:08
UsedFuel : 614 kg

Figure 3.6: Constant 10 kt tailwind

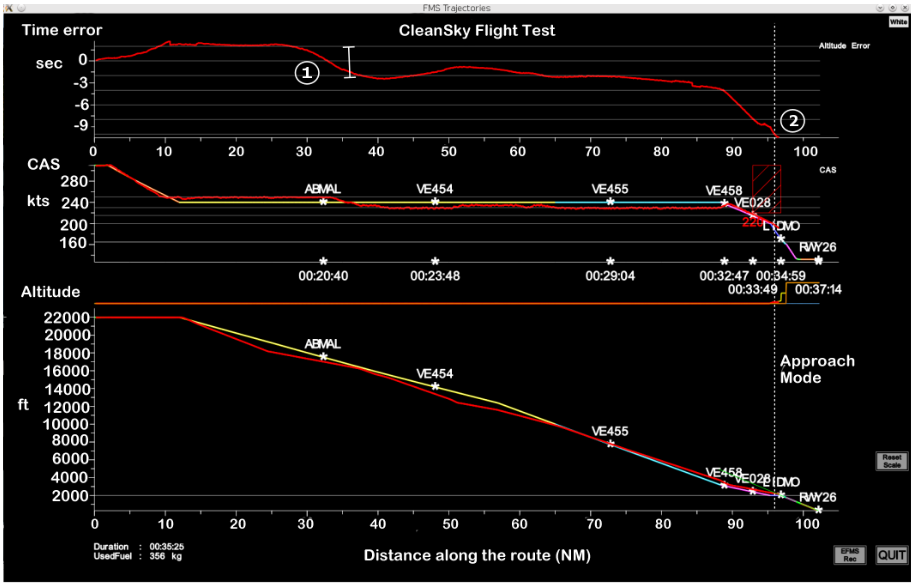


Figure 3.7: Gusting 10 kt tailwind

Performing the same analysis on the headwind scenarios (Fig: 3.4.3. and Fig: 3.4.3.), similar results can be observed. In **(3)** the time error caused by the turn is higher when gusting wind is present. The overall time deviation is similar in both cases reaching an approximated value of 6 seconds late. When compared with the tailwind scenarios, the time error is higher in the ones encountering tailwind.

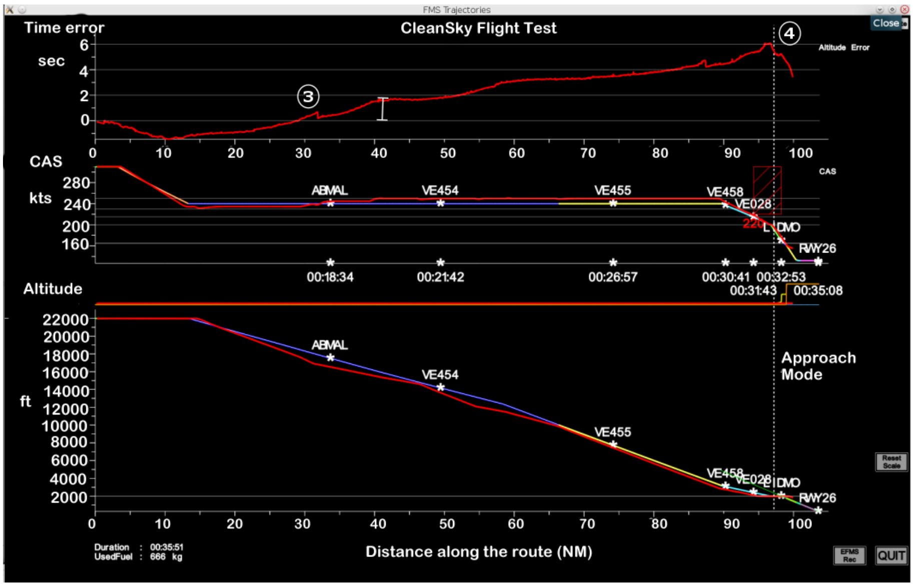


Figure 3.8: Constant 10 kt headwind

As in the no-wind scenarios, the steep descent of the aircraft creating a non-idle descent is also present in these simulation runs. This phenomenon will not be discussed again as it has been already mentioned in the previous section.

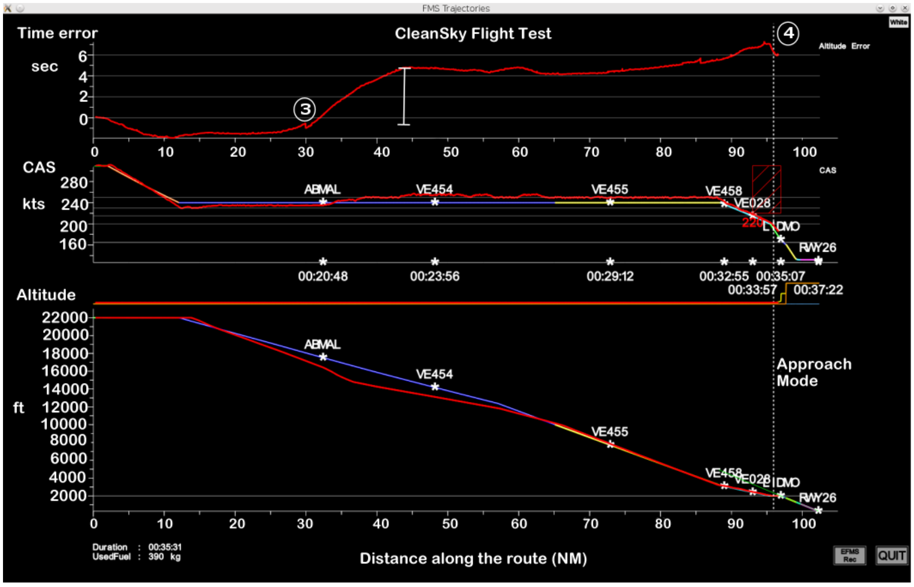


Figure 3.9: Gusting 10 kt headwind

3.4.4. Main issues and recommendations

The issues encountered in the previous section are further discussed and analysed with the objective of finding an appropriate solution to each one of them.

A summarized table of the issues and observations is given below.

Issue	Description	Possible solution
Initialization condition	Whenever a trajectory is generated, the guidance module must be reset to offer a proper guidance information	A simple programme that enables the guidance automatic reset has to be implemented. The pilot's tasks should not involve the manually reset of the guidance module.
Turns	A peak in time error is observed whenever the aircraft is performing a turn. The time error noticed always results in a late performance of the aircraft	A study of the effect of the bank angle, change in track angle, and the speed in each one of this turns has to be made. If a proper relation between all these parameters is found, the controller could be adjusted to compensate these time errors.
Steep descent	While in descent, the aircraft vertical trajectory goes beneath the initial computed altitude trajectory due to a steeper than normal descent.	This behaviour has been attributed to the simulation environment itself, the proper idle descent that the aircraft is able to perform following the controller indications, will be proven through a secondary simulation environment with more accurate aircraft performance data.

3.4.4.1. Turns

For our study, a simple rule of thumb is trying to be achieved in order to compensate the time error generated when the aircraft is performing a turn. Although the turns along the trajectory are performed during descent or climb, for our purpose an approximation to a levelled bank turn is considered.

First of all, an introduction to the basic banked turn equations is presented. From Newton's Second Law it is known that any unbalanced force results into an acceleration of the object upon which the force is applied that is proportional to its mass (*F=ma*). Drawing the main forces acting on the aircraft while it is performing a banked levelled turn we obtain:

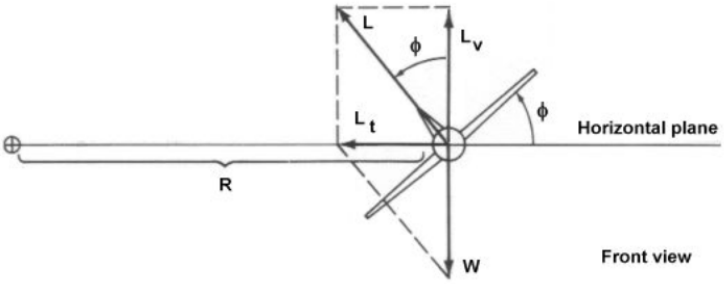


Figure 3.10: Forces on a levelled banked angle turn. Source: [30]

where *L* is the total lift with it's corresponding vertical (L_v) and turning or horizontal components (L_t), *W* is the weight of the aircraft, *R* is the radius of turn and Θ is the bank angle.

From the schematic draw, it can be observed that the uncompensated force that will cause the aircraft to change its heading and turn is the horizontal lift component that in terms of the bank angle equals to:

$$L_t = Lsin(\Phi) \tag{3.1}$$

By applying the Second law of Newton to this expression and knowing that the centripetal acceleration is proportional to the squared speed and inversely proportional to the radius of turn, we obtain:

$$Lsin(\Phi) = ma \tag{3.2}$$

$$L\sin(\Phi) = \frac{W}{g} \times \frac{V^2}{R} \tag{3.3}$$

In the vertical plane, the following expression guarantees vertical equilibrium:

$$L\cos(\Phi) = W \tag{3.4}$$

Therefore, an expression of the radius of turn in terms of the aircraft speed and the bank angle can be found:

$$\tan(\Phi) = \frac{V^2}{gR} \tag{3.5}$$

$$R = \frac{V^2}{g\tan(\Phi)} \times k \quad [NM] \tag{3.6}$$

where V is the true airspeed (TAS) of the aircraft and k a constant through which the obtained radii is given in NM.

Going back to the controller aspect, the way the time error is calculated needs to be explained in order to know how to compensate it. When computing the time error, the controller takes into account the lateral deviation of the aircraft when compared with the initial computed trajectory. When turning, this deviation increases and the aircraft performs the turn within a bigger radius than predicted causing an increment in the time error. As the controller seizes an increment in the late area of the time error, it automatically advises a higher speed, and as it is shown in equation 3.6, this results in an even higher radius of turn and a higher time error as the lateral deviation is even bigger.

By knowing how the speed, the bank angle and the track angle change affects the time error, we could introduce this knowledge into the controller and try to compensate the time deviation. Having the radius of turn, the time it takes the aircraft to perform the turn given a certain bank angle, speed, and track angle change can be known:

$$d = \frac{2\pi r\alpha}{360} \quad [NM] \tag{3.7}$$

$$t = \frac{d}{V} \quad [s] \tag{3.8}$$

where α is the track angle change in degrees.

To be able to introduce the effect of the speed, bank angle and track angle change on the resultant radius of the turn, the following graphics (Fig.3.11 and Fig.3.12) have been created.

It has to be highlighted that the parameter used in the graphics below is the TAS deviation and not the TAS of the aircraft itself, understanding by TAS deviation as the difference between the initially planned speed and the one advised by the controller. This was done with the intention of seeing how sensible was the time error to the speed deviation under different bank angle and track change situations. It must be mentioned that even if TAS speeds are taken into account in this particular graphics, the controller speed advisories are CAS values. Therefore, the CAS-TAS conversion error has been neglected in this case as only a general, broader idea was needed.

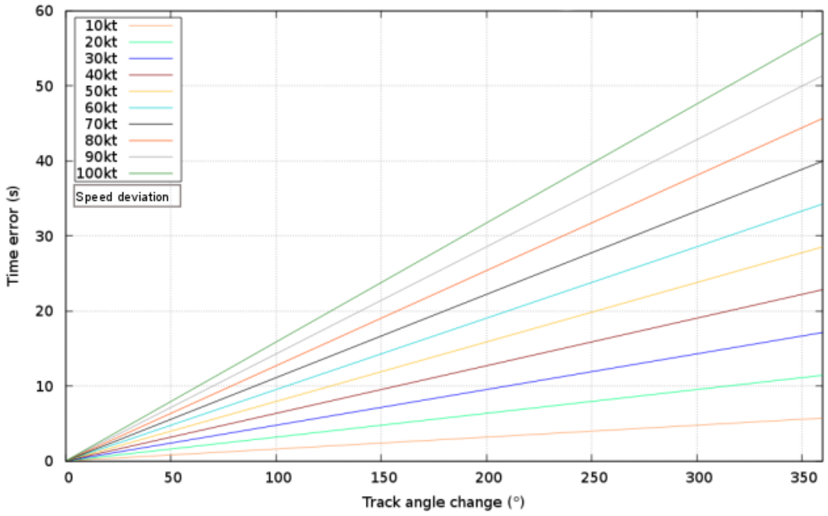


Figure 3.11: Time error vs Track Angle change with different speed deviation values

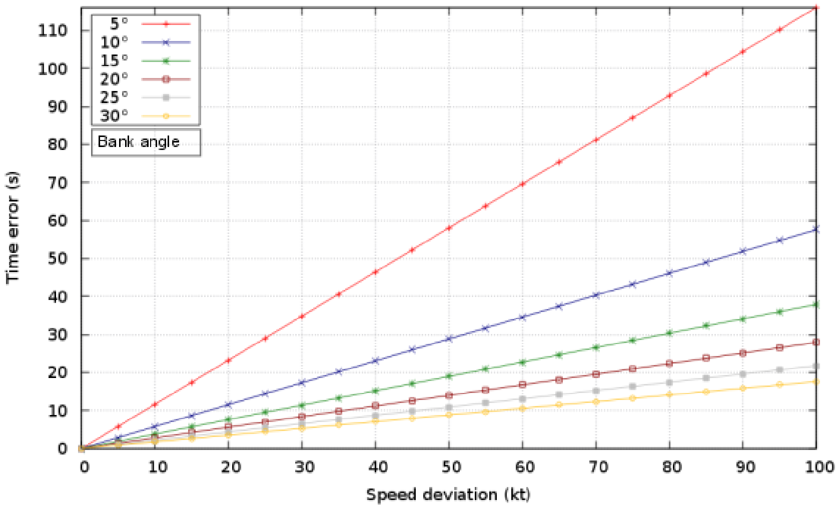


Figure 3.12: Time error vs Speed deviation with different bank angle values

It can be noticed that a certain speed deviation has a greater effect on turns with smaller bank angle and higher track angle change. The solution proposed is then to try and compensate the time error created by a specific turn by using these equations. Initial trials with this method still showed problems when the aircraft overshoots during turns. This happens when the aircraft is late and the controller advises a higher speed to compensate the time error. By flying faster than planned the radius needed to perform the turn is higher, the distance to travel is then also higher and the aircraft is even later. Such an error augmentation has to be avoided. The 4D-Controller will be disengaged in these situations to avoid the increase of time error. When the turn is completed,the 4D-Controller will be engaged and the time error will be minimised again.

CHAPTER 4. SECOND SIMULATION ENVIRONMENT. THE ATRA PRE-FLIGHT TESTBED

4.1. Simulation software and interfaces

The second part of the project includes a new set of simulation runs with a DLR developed simulator, the ATRA pre-flight testbed. This simulation environment is frequently used to test novel systems before the real flight tests as it models with great accuracy the experimental aircraft performance. Real data of the experimental aircraft has been gathered during flight tests and used in this simulation software.

This simulation environment does not include a realistic graphic interface neither a simulation of the sceneries as in X-Plane. The simulation software is ran in a PC and a real FCU is used to introduce the parameters given by the controller and guide the aircraft along the time constrained idle descent. As in previous simulations, an advanced HMI display (See Figure 3.2) is available to visualize the lateral trajectory of the aircraft. The CAS and altitude profiles as well as the time and altitude resulting errors are available on the FMS trajectory display (Fig. 3.3). As before, the controller guidance parameters are shown on a separated display.

4.2. Assumptions

Throughout all the simulation runs performed with the ATRA pre-flight testbed, a modification of the controller has been made. The strategy through which the controller chooses to satisfy the restriction of flying at a maximum speed of 250 kt below FL100 is different when compared with the previous simulation runs.

In order to test which strategy gives better results and in order to be able to contrast these results further on with the pilots executing the real flight test, different approaches are tested. Within these simulation runs, the initially planned altitude profile contains a level off stage at FL100 to allow the aircraft to decelerate. When compared with previous simulations where the aircraft descended from the ToD directly to 2000 ft, now the aircraft descends from the ToD to FL100 and then to the approach altitude of 2000 ft. By using this second strategy we assume a certain input of thrust that allows us to maintain the aircraft at a constant altitude.

4.3. Definition of scenarios

The main objective of these second simulation runs is to obtain a more varied sample of the controller behaviour when exposed to different forecast wind errors. Additionally, an improved performance model of the real flight test aircraft is used and therefore a more accurate idle descent should be achieved when compared with the first simulation environment.

All scenarios simulated use the RWY26 to land and start in cruise at ABMAL waypoint (See Table 2.3.). The lateral trajectory simulated is shown in Figure 4.1.

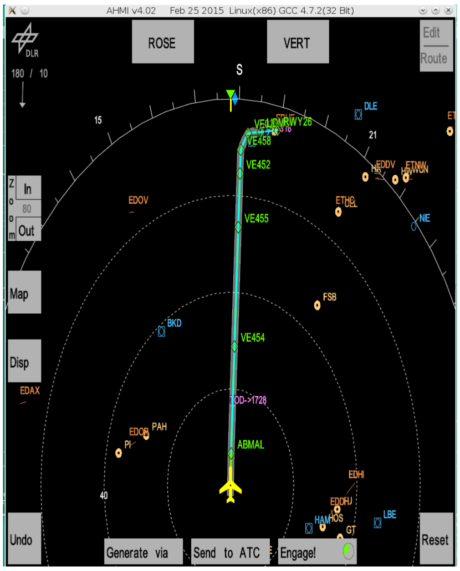


Figure 4.1: Lateral Trajectory Simulated (RWY26)

In this case, only one runway direction is simulated as it has been considered that the controller's behaviour has no dependency on the chosen runway direction.

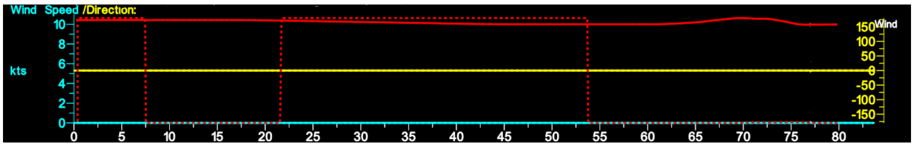
The following cases have been simulated and analysed:

Scenario #	Simulated wind	FMS introduced wind
Baseline	0 kt	0 kt/ 0°
Scenario 1	10 kt/ 180°	0 kt/0°
Scenario 2	10 kt /0°	0 kt/ 0°
Scenario 3	Real wind	0 kt/ 0°

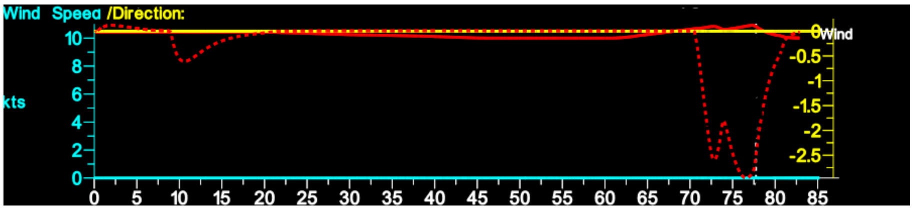
It can be seen that the wind taken into account when first computing the initial trajectory is always zero. A first scenario with no wind is then simulated in order to see the controller's answer in this new simulation environment and to serve as a baseline for the further simulations. Then, a constant 10 kt headwind and tailwind is simulated. Finally, a real weather recorded file is used and real weather phenomenons with gusting wind is simulated. The file was recorded in 5th of May of 2014 during a flight test.

A view of the simulated and planned wind for each scenario can be seen in Figure 4.2.

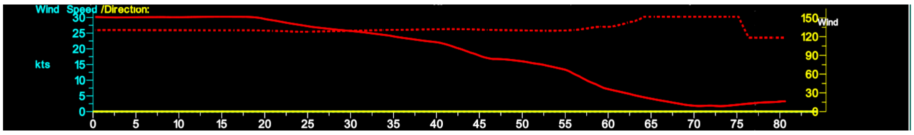
The blue and the yellow line represent the wind speed and direction taken into account by the FMS. The red thick line represents the actual wind speed encountered during the descent, while the dotted red line represents the encountered wind direction. All these parameters are represented along the x-axis corresponding to the distance to go in NM.



(a) 10 kt Tailwind



(b) 10 kt Headwind



(c) Real wind

Figure 4.2: Simulated wind scenarios

4.4. Discussion of results

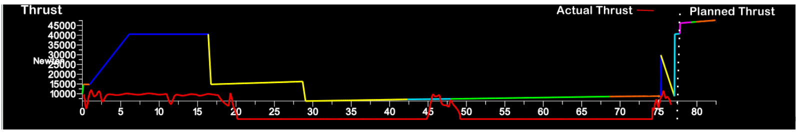
As in the previous simulation environment in this section the observations made regarding the controller's behaviour are exposed. Again, numbers have been used to empathize a certain segment of the graph that provides valuable information of the controller.

4.4.1. No Wind Scenario

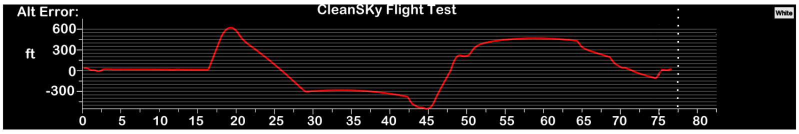
The results obtained from the previously mentioned scenarios are detailed in this section. First, the baseline situation with no wind is analysed.

As seen in Fig: 4.3(c), both the speed profile and the altitude profile are followed with good accuracy. The time error oscillates between ±1 second along the descent and gets a final value at the FAP LIDMO of approximately -3 seconds (early arriving). The altitude error is at every moment lower than the ±1000 ft boundary, deviating a maximum of 600 ft from the planned trajectory Fig: 4.3(b). It is worth noticing that within this simulation environment, the aircraft is capable of descending idle following the initial altitude profile. The steep descent behaviour noticed in the previous simulation environment is not present here.

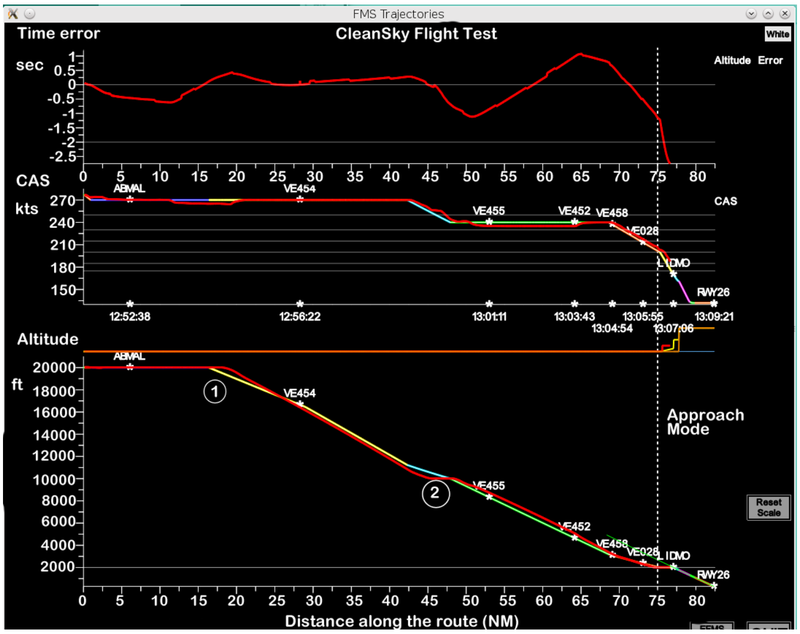
The baseline simulation is also showing that although the ToD has been selected in the moment indicated by the controller, a late response of the aircraft is present. Therefore, as seen in **(1)** the altitude trajectory flown is slightly above the planned one. Additionally, the mentioned stabilization phase at FL100 is observed in **(2)**. As to comply with the restriction of flying at a maximum speed of 250 kt below FL100, the aircraft descents from ToD to FL100 where it maintains its altitude while decelerating to 240 kt. In this part of the descent, thrust inputs are present that enable the level flight as seen in Figure 4.3(a). The rest of the descent is flown in idle.



(a) Planned and actual thrust input



(b) Altitude error (ft)



(c) Time error, Speed profile and Altitude profile

Figure 4.3: No wind Simulation

4.4.2. Constant Wind Scenarios

Before simulating these constant wind scenarios, a couple of changes have been made to the controller as a result of observations from the previous run.

1. In order to produce a more accurate scenario and obtain better results, the Approach Mode advisory has been changed during these constant wind simulations. Until now, the controller was displaying the Approach Mode advisory at a constant 15 NM distance from the runway. This parameter was chosen in order to simplify the controller's algorithm and to be able to cope with different trajectories. For the following simulations, the Approach Mode advisory is given at the FAP, in this case the LIDMO waypoint. Therefore, the guidance will remain operative for a longer period of time in comparison with the past simulations.

2. The ToD advisory given by the controller is shown a few seconds earlier to compen-

sate the late answer of the aircraft.

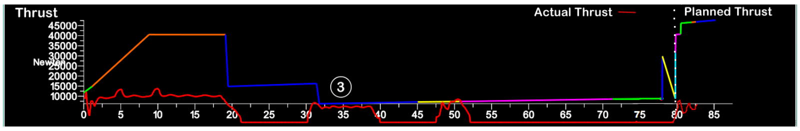
In these constant wind simulations, the effect of a later or earlier descent than indicated by the controller is also analysed. An early descent towards FL100 is simulated during the tailwind scenario, whereas a late descent to 2000 ft is simulated during the headwind scenario. These situations can occur during the real flight test, as a consequence, the controller's behaviour needs to be studied.

When analysing the headwind scenario several phenomenons occur:

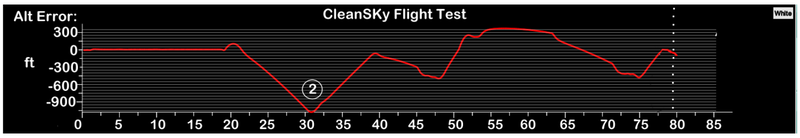
- The unexpected headwind encountered causes a decrease of the total energy of the aircraft that results in the controller advising higher than planned speeds along the whole trajectory (Fig: 4.4(c)). To compensate the 10 kt constant headwind the controller advises an increase of 5-10 kt.
- As seen in **(1)**, the higher speeds cause the lower altitude trajectory that reaches the allowed deviation limit of 1000 ft in **(2)** (Fig: 4.4(b)).
- Thrust inputs are needed in order to correct the negative altitude deviation **(3)** (Fig: 4.4(a)).
- After the level off at FL100, a late descend towards the approach altitude of 2000 ft is simulated. The direct consequence of descending later than advised by the controller in presence of headwind is that the trajectory flown is now higher than the initially planned one. This behaviour is not the usual when flying in presence of headwind.
- In this final stage of the descent, the altitude error takes positive values. Nevertheless, these errors are not big enough to cause a speed-brake input.
- In the presence of forecast errors, the altitude error is higher than the no wind scenario. This result is clearly logic as to compensate the time errors the altitude errors are increased.
- As in the baseline, a level off at FL100 **(4)** exists (Fig: 4.4(c)) and its corresponding thrust input.
- The time error at the FAP is approximately 3 seconds early.

Regarding the tailwind scenario, the following remarks are done:

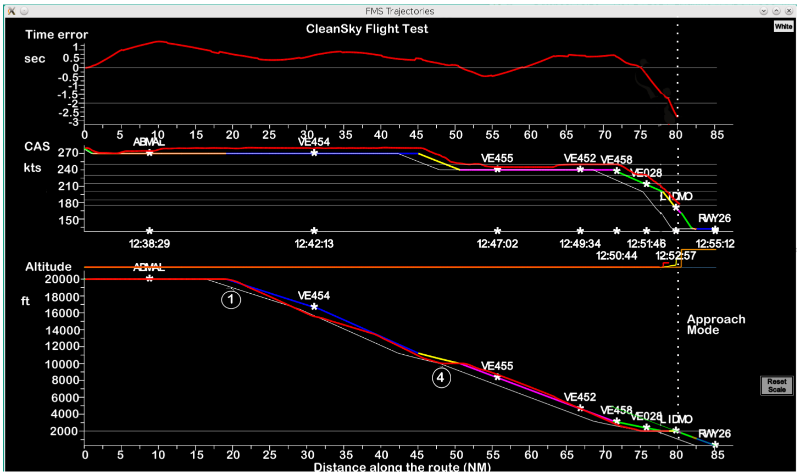
- First of all, by encountering unexpected tailwind, it can be seen that the controller advises lower speeds all over the trajectory in order to compensate the 10 kt tailwind.
- The early descent from the ToD can be seen in Fig: 4.5(c) in **(1)**. This causes that even if the aircraft encounters unexpected tailwind and decreases the speed to compensate it, the vertical trajectory that is actually flown is lower than the planned one. Encountering an unexpected tailwind increases the total energy of the aircraft, so as can be seen, the controller advises lower speeds. Recalling the conservative



(a) Planned and actual thrust input



(b) Altitude error (ft)

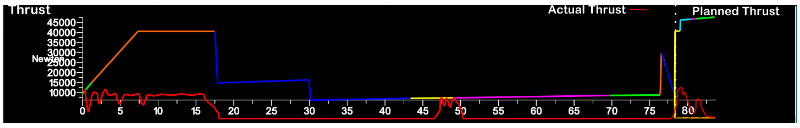


(c) Time error, Speed profile and Altitude profile

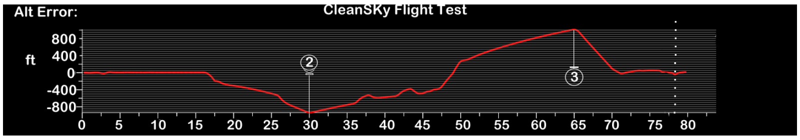
Figure 4.4: Constant 10 kt headwind scenario

energy change, a lower speed should give place to a higher altitude. Nonetheless, the opposite happens in this first part of the simulation. Due to the an early descent from the ToD the observations made during the simulation does not correspond to the usual situation encountered in presence of constant tailwind.

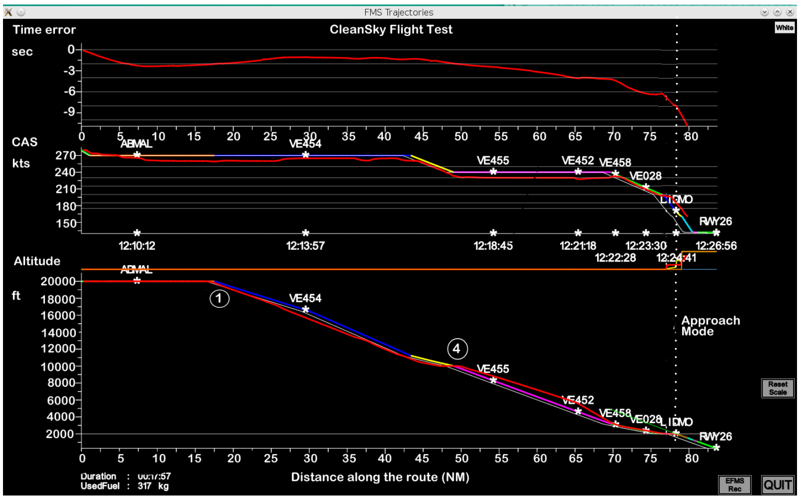
- The altitude error in the first part of the simulation reaches quite high values (2). Nonetheless, the controller is able to compensate them without the need of a thrust input as seen in Fig: 4.5(a). Along the descent, the lower than planned speeds are expected to create a positive altitude error as it happens in **(3)** (Fig: 4.5(b)).
- As seen in **(4)**,the tailwind component results in a positive altitude error while descending to 2000 ft, that needs to be corrected by speed-brakes input **(3)**.
- The time error along the trajectory is maintained around 3 seconds early and takes a value of approximately 8 seconds early at the FAP.
- Similar to the headwind scenario, the decrease in speed advised by the controller to compensate the forecast error takes values of 5 or 10 kt.



(a) Planned and actual thrust input



(b) Altitude error (ft)



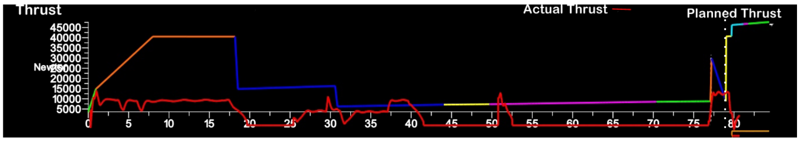
(c) Time error, Speed profile and Altitude profile

Figure 4.5: Constant 10 kt tailwind scenario

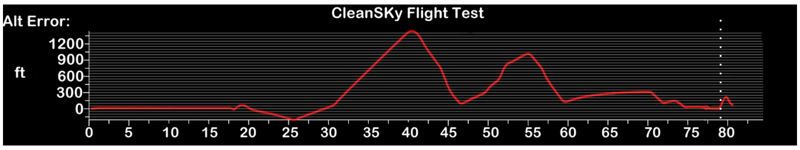
4.4.3. Real Wind Scenario

In the scenario where real, gusting wind has been simulated, the following observations have been made:

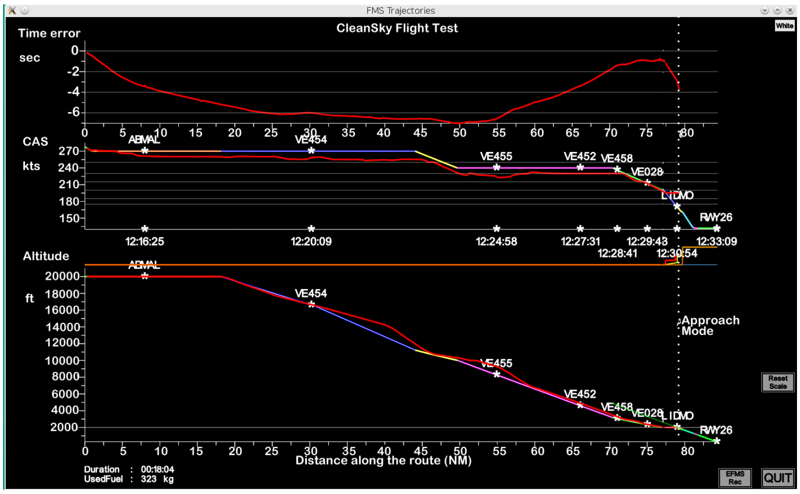
- As shown in Fig: 4.2(c) and as seen in the CAS graph in Fig: 4.6(c) the simulated wind has a main tailwind component. As a result, the CAS advised by the controller is lower than the planned one.
- As the strength of the wind decreases with altitude, the difference between the planned CAS and the actually flown one is slightly smaller as it descends.
- The lower advised CAS results in positive altitude errors that reach the deviation boundary of 1000 ft in two occasions (Fig: 4.6(b)). Therefore, speed-brake inputs are needed to correct the vertical trajectory.
- Along the final part of the descent, at lower altitudes with weaker wind component, the controller is able to correct the time deviation up to approximately one second early. Nevertheless, during the deceleration process the time error increases again reaching a value of 4 seconds early at the FAP.
- Multiple thrust inputs are noticed before FL100. Due to an error or bug of the software a constant 1900 ft/min descent rate was activated along this segment. 4.6(a)



(a) Planned and actual thrust input



(b) Altitude error (ft)



(c) Time error, Speed profile and Altitude profile

Figure 4.6: Real wind scenario

4.5. Main issues and recommendations

This section contains the main observations and improvements made to the controller after the second simulation environment.

The overall behaviour of the controller among these simulations has been satisfactory. The time error at the FAP has been smaller than 10 seconds in each case. The maximum time error corresponds to the scenario with 10 kt constant tailwind.

After the baseline simulation, the controller has been improved by changing the moment at which the approach mode is engaged. This change makes the simulation more accurate to the real situation. Although the guidance is now active during a longer period of time, the difference is small and therefore no significant performance change is noticed.

Within the simulations containing a later or earlier descent the effects of doing so are significant. Descending earlier in presence of tailwind causes negative altitude errors while a late descent in presence of headwind causes positive altitude errors. These late or early descents result in a mix of typically headwind or tailwind behaviour causing a thrust input in presence of tailwind or a speed-brake input in presence of headwind. Although the controller can successfully cope with these errors, it is recommended that the pilots descend accurately when advised in order to avoid unnecessary thrust or speed-brake inputs.

Due to the error encountered in the realwind scenario simulation and although the results and overall performance of the controller is satisfactory, this run can not be completely taken into account as no idle descent was initiated and vertical speed mode was activated. A good pilot briefing and pilot training simulations are recommended before the flight test in order to check that all the adjustments made along this project solve the small encountered issues.

CONCLUSIONS

The 4D-Controller tested through different simulation environments enables accurate time constrained continuous descent operations (CDOs).

The results of both simulation environments have shown a time accuracy at the metering waypoint of less than 10 seconds. Simulating different wind forecast errors highlighted the strong dependency between these forecast errors and the level of time and altitude deviations from the initially planned profiles. The worst case scenario has been in both environments the simulations that included an unexpected tailwind. It has been noticed that even in zero wind scenarios the tendency is to have a negative time error, meaning an early arrival. If unexpected tailwind is now added, it is clear that this will increase even more the time error by arriving even earlier.

Regarding the frequency of speed advisories change, the 5 kt increment has given good results. The real-time simulations showed no significant workload due to the speed changes. Peaks in the frequency of the changes are located during the decelerating phases as expected. The deceleration from higher speeds results in several 5 kt continuous changes. It should be remembered that these advisories are not mandatory and therefore the pilot in this cases could simply sum up 5 kt changes and introduce them directly in the FCU and lower the workload. Future studies could be performed using a higher difference between the CAS changes and a lower frequency. This could be very beneficial while flying at high speeds but must be carefully studied while flying at almost approach speeds as the accuracy needed is higher.

It has been proven that using thrust and speed-brakes inputs to correct the altitude deviations the aircraft can perform the descent following the initially trajectory without the need of a re-plan. The amount of thrust and speed-brakes needed depends on the accuracy of the initially planned trajectory and the magnitude of meteorological forecast errors.

Flying curved descents was another objective of this project. As seen from the first environment simulations, the controller is capable of guiding the aircraft along a curved trajectory. Nevertheless, small time deviations arise as a result of high lateral errors. The accuracy of the lateral trajectory is lower during a turn, so additional time errors of maximum 2 seconds appear. Although the errors caused by the turns are not significant in the case of the simulations ($\leq$ 2 s), it has been decided to stop the guidance while the aircraft performs the turn during the flight test. In real flight conditions these time errors could be higher as the lateral errors could also be higher.

Within these simulation trials two different strategies have been tested to fulfil the speed restriction at FL100. No significant difference in the performance was noticed. Nevertheless, one of the options requires a constant altitude phase that requires a certain amount of thrust. This option is safer as it assures that the aircraft will satisfy the constraint no matter the environmental conditions, but reduces the benefits of the idle descent. The final decision on which strategy will be used during the real flight test will take into account the pilots opinions.

Overall, the controller has shown a great capability of adapting to different simulation environments and forecast errors. The issues found in its behaviour have been mitigated and no concerning errors exist at the present. Nevertheless, the future flight test will reveal how the controller will react under real weather conditions and how pilots react to this new guidance option.

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APPENDICES

APPENDIX A. EDVE SID AND APPROACH CHARTS

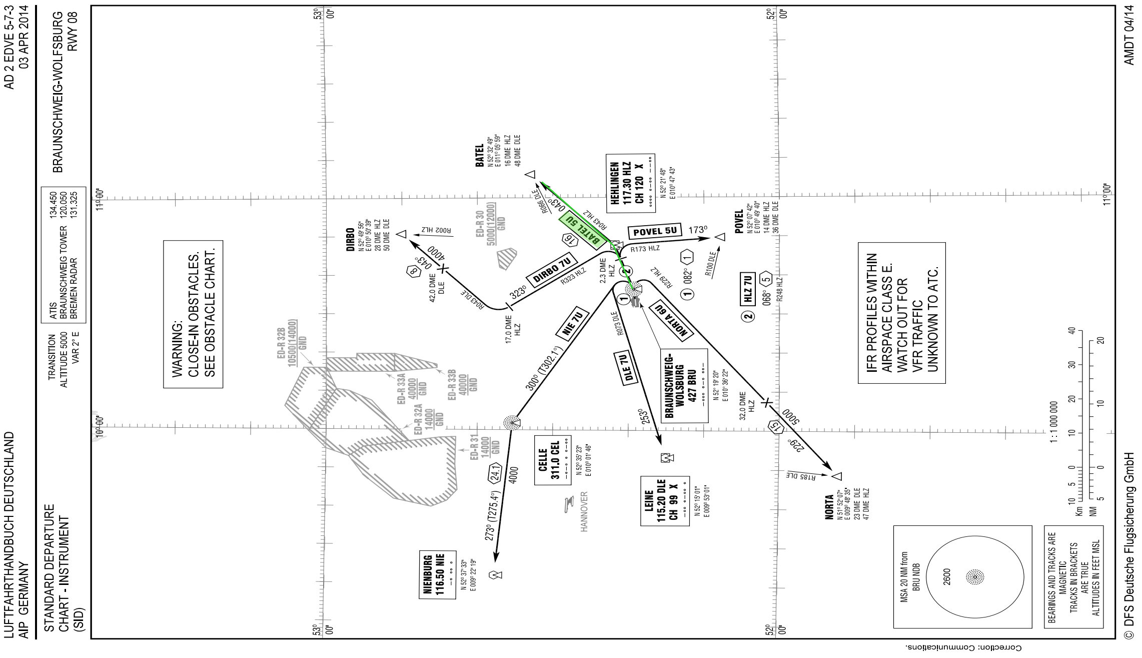


Figure A.1: SID Runway 08

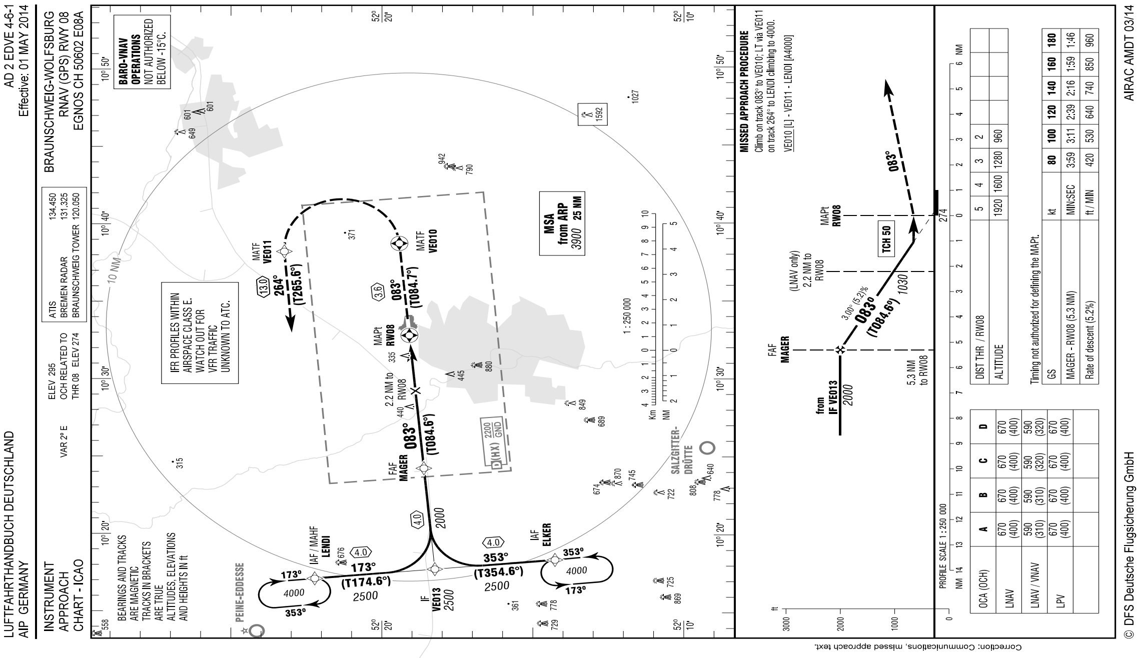


Figure A.2: Approach Runway 08

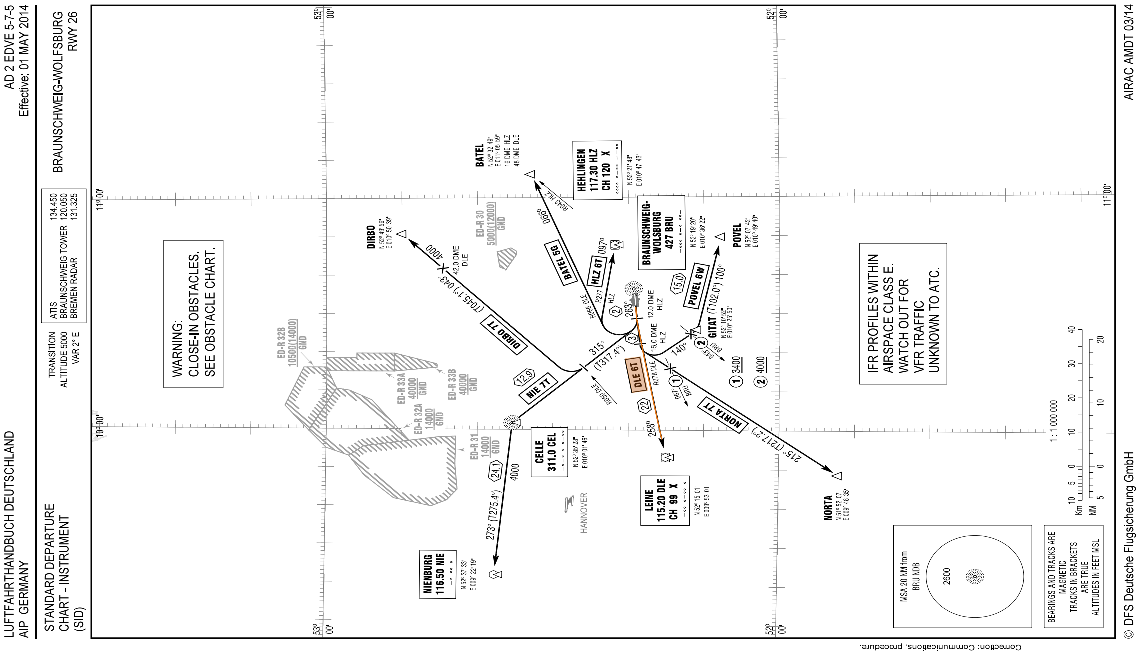


Figure A.3: SID Runway 26

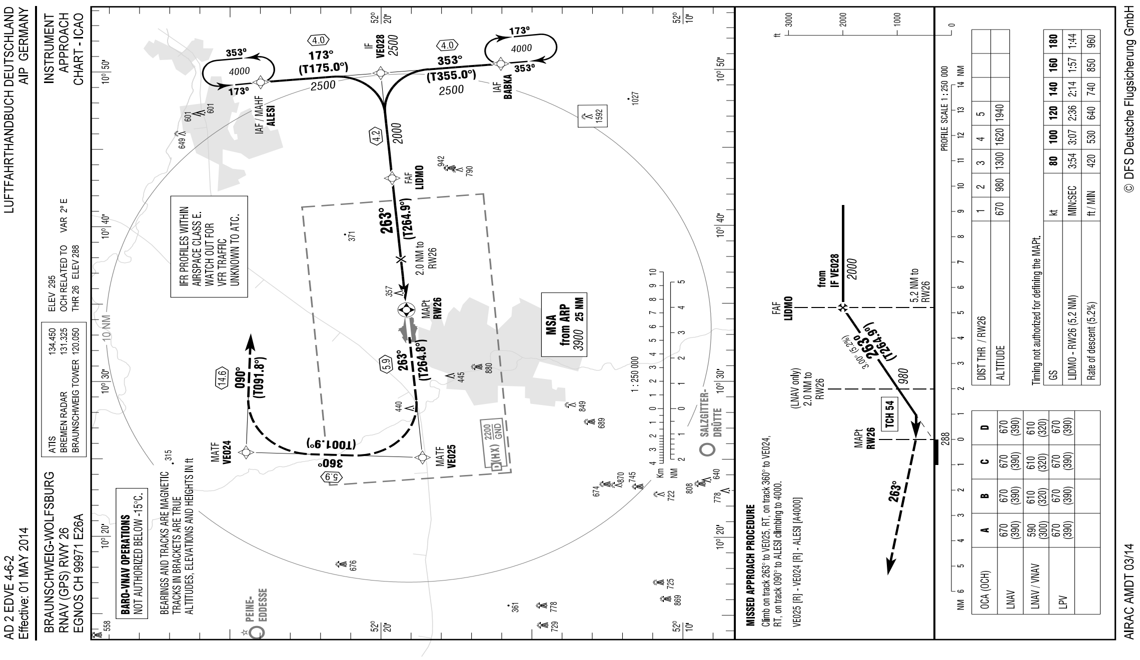


Figure A.4: Approach Runway 26

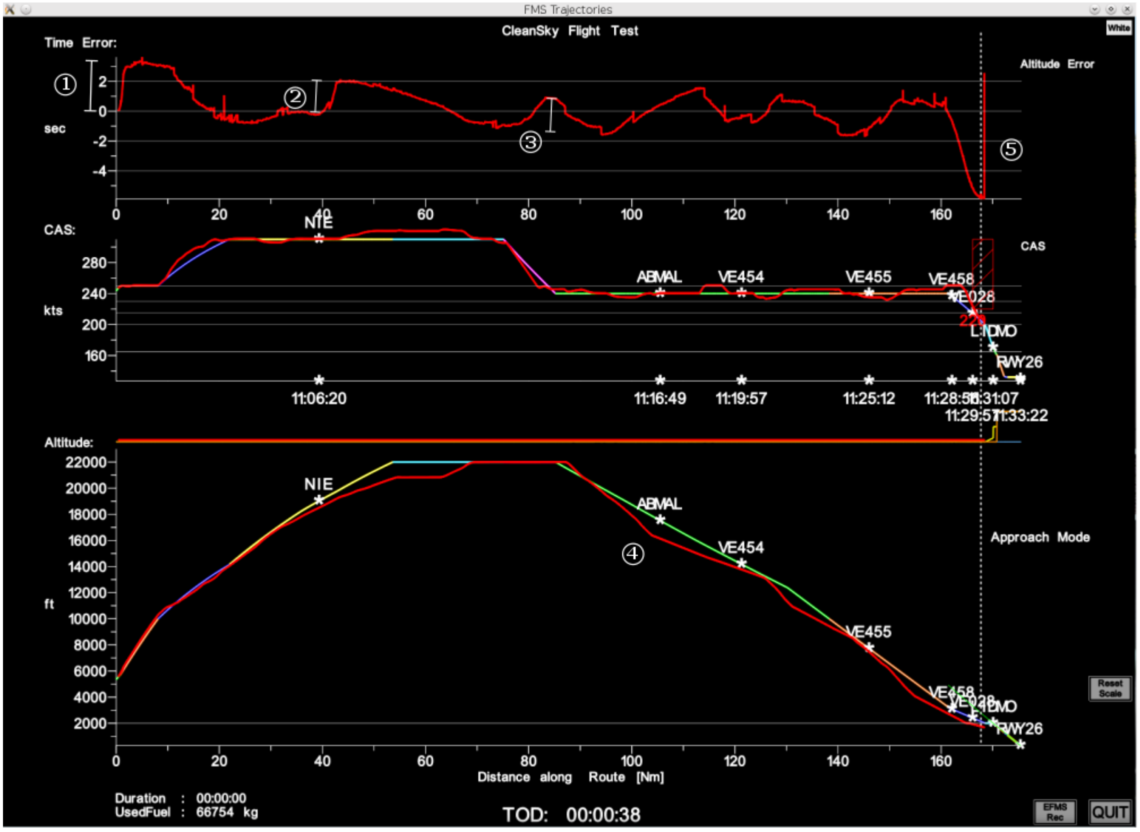
APPENDIX B. A329 PERFORMANCE AND OPERATIONAL RESTRICTIONS

Speed restrictions	
Maximum operational speed	
SL- 24.600 ft	350 kt
24.600- 39.000 ft	M0.82
Maximum turbulence penetration speed	
Below FL200	250 kt
Above FL 200	275/M.76
Max speed below FL100	250 kt
Max flap/slats configuration speeds	
Config 1	230 kt
Config 2	210 kt
Config 3	185 kt
Full	177 kt
Max speed with landing gear extended	280kt/M.67
Max speed at which landing gear may be extended	250 kt
Max speed for landing gear retraction	220 kt

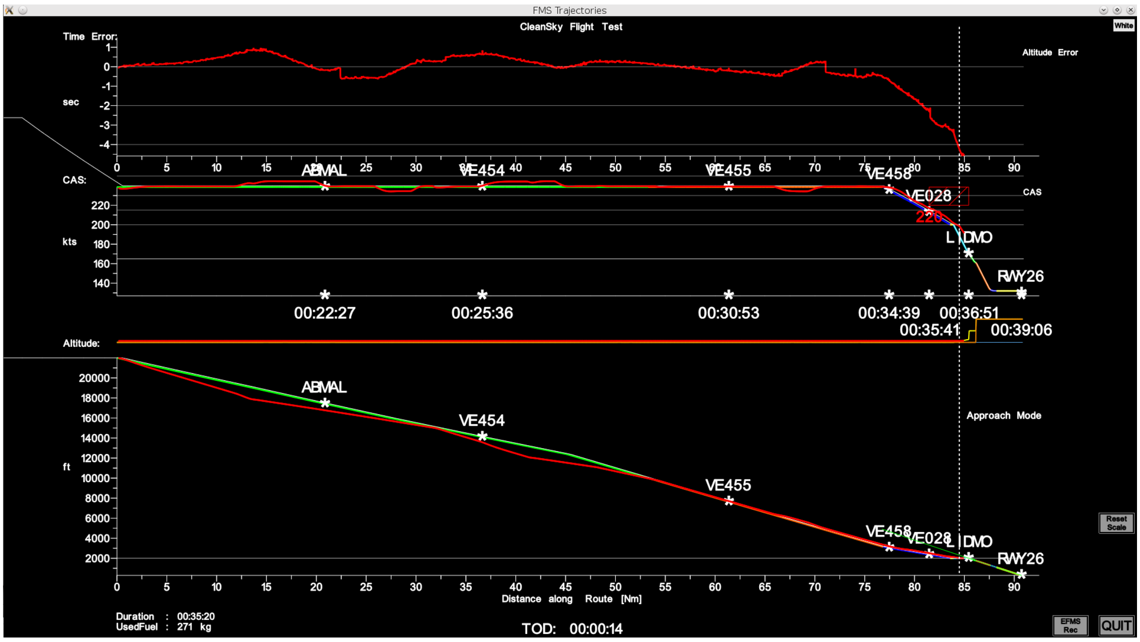
Altitude restrictions	
Maximum altitude	39.100 ft
Max Flaps/Slats extended Altitude	20.000 ft MSL
Max altitude landing gear can be extended	FL250
Max altitude APPR engaged	8.000 ft

APPENDIX C. FIRST SIMULATION ENVIRONMENT GRAPHICAL DATA

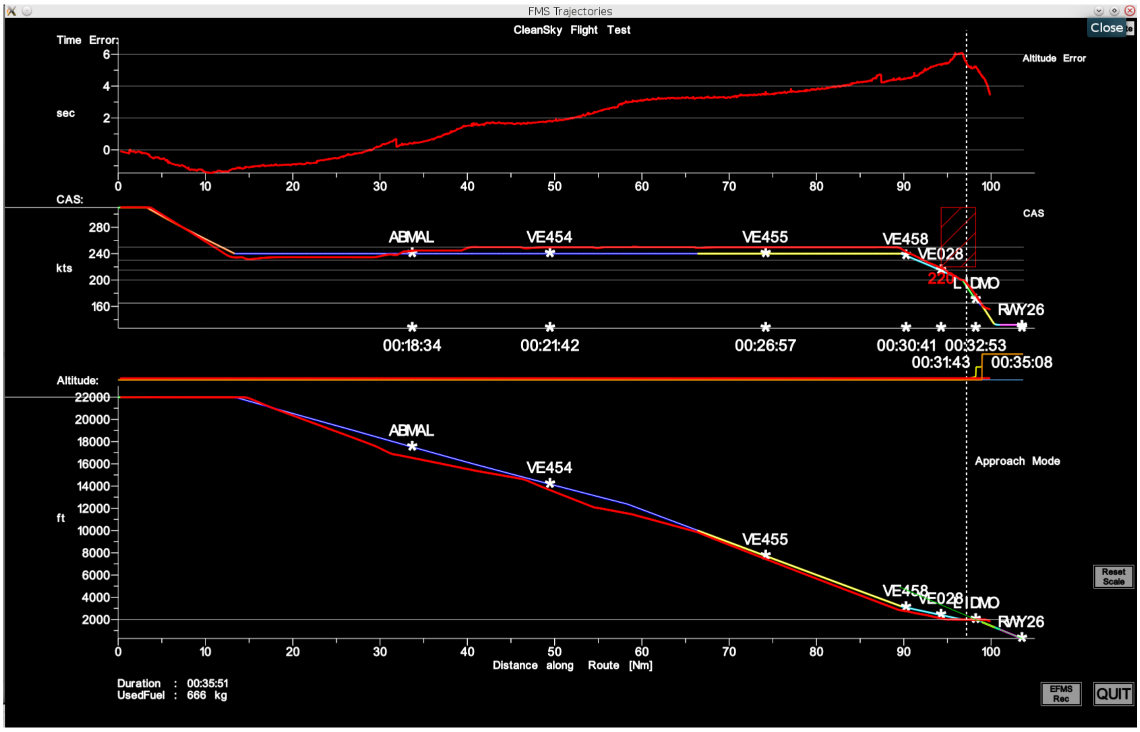
RUNWAY 26



(a) RWY26-HITL-No Re-plan- No wind

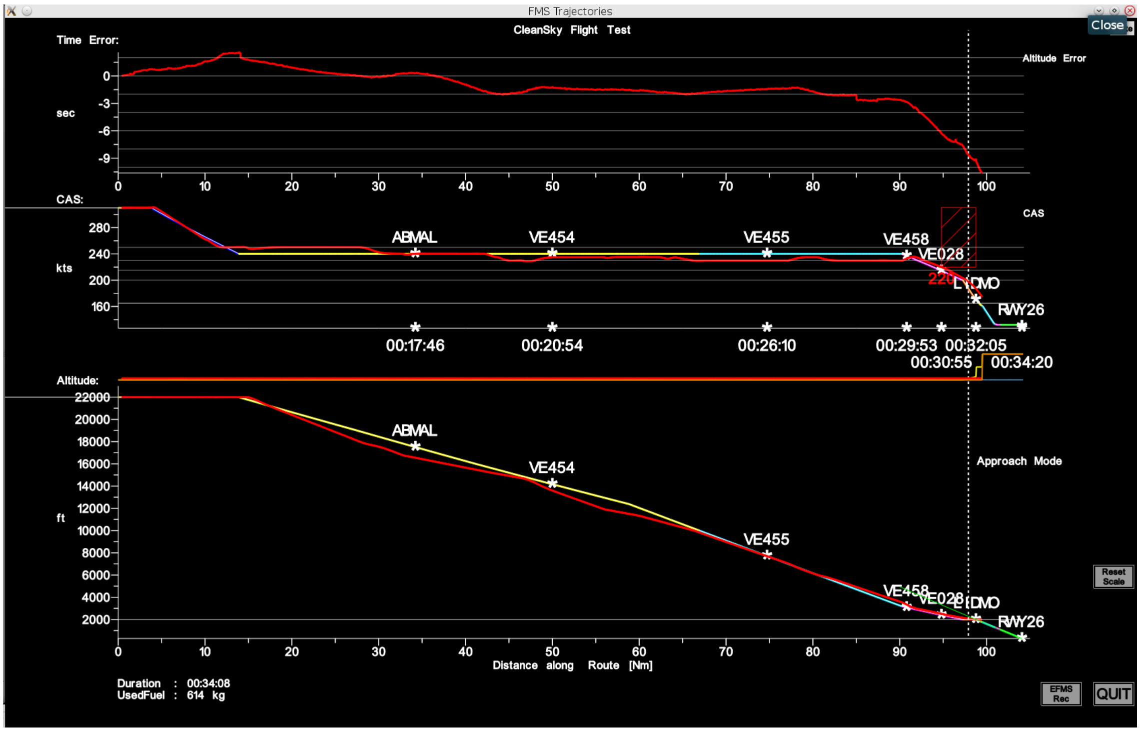


(b) RWY26-HITL-Re-plan- No wind



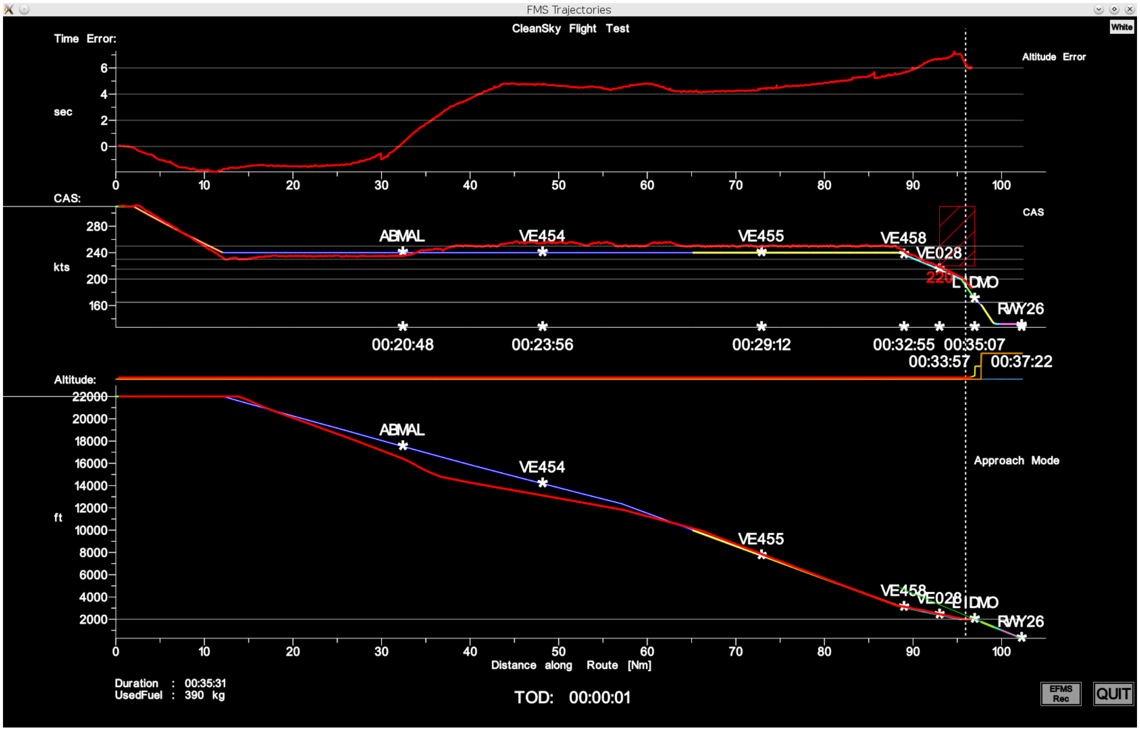
Duration : 00:35:51
UsedFuel : 666 kg

(c) RWY26-HITL-Re-plan- 10 kt Constant Headwind

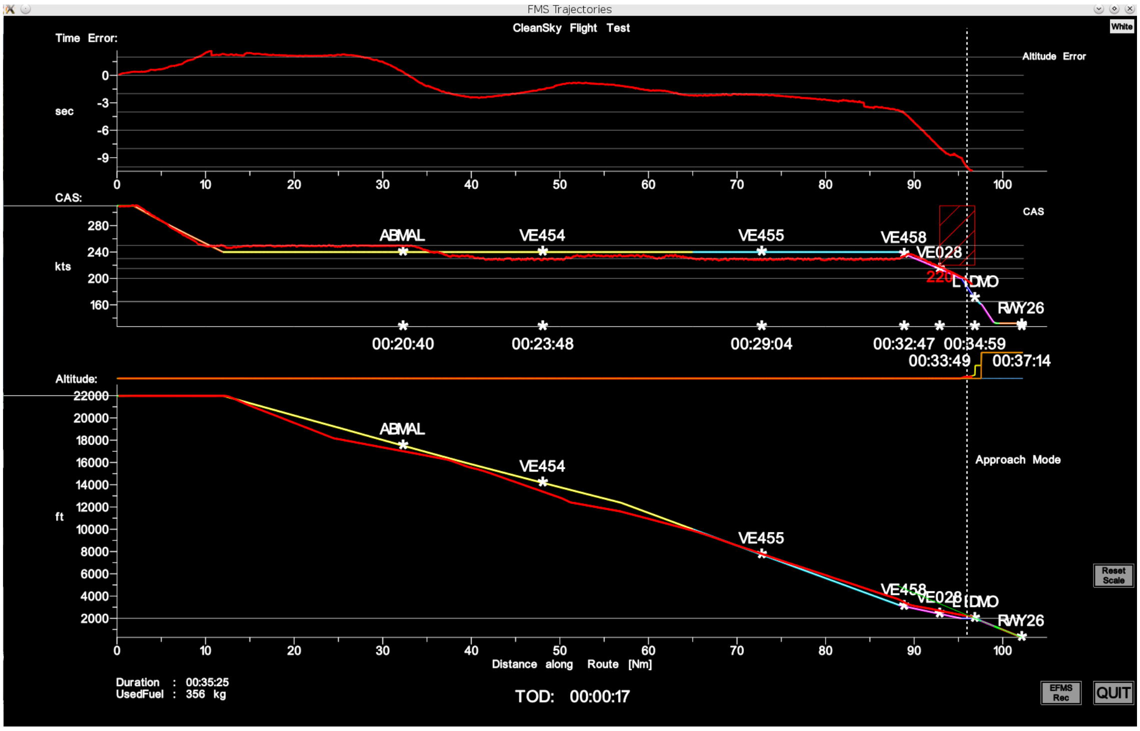


Duration : 00:34:08
UsedFuel : 614 kg

(d) RWY26-HITL-Re-plan- 10 kt Constant Tailwind



(e) RWY26-HITL-Re-plan- 10kt with 3 kt Gust Headwind



(f) RWY26-HITL-Re-plan- 10kt with 3 kt Gust Tailwind